THEORY AND OPERATION

OF

DIRECT-CURRENT MACHINERY

ENGINEERING EDUCATION SERIES

THEORY AND OPERATION

OF

DIRECT-CURRENT MACHINERY

PREPARED IN THE
EXTENSION DIVISION OF
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BY

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PREFACE

In his instructional work the author has to deal with students of limited mathematical training. To meet the needs of this work this text has been prepared. Although it was thought inadvisable to omit mathematics entirely, only the more elementary principles used are, and these merely to make clearer the quantitative relations of the physical quantities involved in the theory of direct-current machines. In connection with the limited use of mathematics, an attempt has been made to explain the principles involved so fully that a reader unable to follow the mathematical solution, may still acquire some understanding of the subject. Whether this result has been attained, the reader will have to be the judge.

The author wishes to express his appreciation of the unfailing courtesy of manufacturers of direct-current machines in answering questions and furnishing material for illustrations. No apology is made for the use of cuts of actual machines and parts where these illustrate the principles and practice under discussion as well or better than line drawings.

Thanks are due Mr. H. E. Kranz for reading the manuscript and for checking the illustrative problems, and also to Mr. Fred R. Jenkins, Chairman N. E. L. A. Committee on Education of Salesmen, for reading the manuscript.

No problems or questions are included in the text, for these are furnished to students separately.

C. M. J.

University of Wisconsin
November 6, 1917.

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THEORY AND OPERATION OF DIRECT-CURRENT MACHINERY

CHAPTER I

FUNDAMENTAL MAGNETIC PRINCIPLES

1. Introduction.—The use of electricity in industries and in homes has increased so rapidly within recent years that, contrary to precedent, there was no separate electrical exhibit at the Panama-Pacific International Exposition. The use of electricity has so permeated the industries that it was not considered advisable to have electrical apparatus and machinery set off by themselves as something apart from other industrial appliances. In fact, instead of having a Palace of Electricity the whole Exposition at San Francisco could properly have been considered as a vast electrical display.

Electrical energy is used not only to operate the mills, shops, and factories, but also to cook, wash, sweep, and to perform many other domestic duties as well as to heat, light, and cool the house.

This extensive use of electricity in industrial and domestic operations makes it highly desirable that not only professional engineers have a thorough knowledge of electrical machinery, but that the layman in electrical matters shall also have a knowledge of the elementary principles and characteristics of electrical apparatus.

The history of the development of electrical apparatus and its use is very interesting. Suffice it to say, however, that this wonderful development has all been made possible by the investigations of Oersted, Ampere, Arago, Faraday, Henry and others in the field of electromagnetism. It was the invention of the electromagnet that has resulted in the immensely varied applications of electricity to the industries, to the transmission of intelligence, and which has produced such remarkable benefits to society. The subjects of magnetism and electromagnetism are thus fundamental in the study of electrical apparatus and machinery.

2. Magnetism.—The essential nature of the property called magnetism is unknown. We only know that under certain conditions a piece of iron, or steel, acquires the property of attracting other pieces of iron by a force which is many times as great as the force of attraction between the two pieces due to gravity, and also that there is a reaction between this property and a like property of the earth which tends to cause the piece

FIG. 1.

of iron to assume a definite position with reference to the earth's meridian, that is, a north and south line.

By magnetism is thus meant the property a body has of attracting iron with a force which is neither gravitation nor due to mechanical action of ordinary matter, and which will tend to set the body in a north and south direction.

This definition clearly does not tell us much about magnetism; it merely enables us to distinguish between magnetic forces and other forces. We thus recognize a magnet by its action. The fact that some substances possess this property has been known for centuries. An iron ore which was first found in Magnesia was first observed to possess this property, and from this the word magnet was undoubtedly derived. This iron ore, commonly called lodestone, which means attracting stone, has no industrial use based on its attracting property.

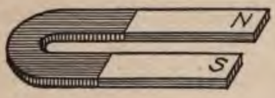


FIG. 2.

3. Magnets.—A body possessing the property of magnetism is called a magnet. The only substance of which commercial magnets are made is iron in some of its forms, although there are other substances that can be magnetized. To this class belong nickel, cobalt, manganese, and an interesting alloy named after its inventor "Heusler's alloy." This is an alloy of copper, manganese, and aluminum. Recently several other such alloys, all containing either manganese or chromium, have been found to possess magnetic properties.

Magnets are made in many different forms. The two common forms of permanent magnets are the bar, Fig. 1, and the horseshoe, Fig. 2.

4. Permanent and Temporary Magnets.—Before the discovery of the relation between magnetism and an electric current, magnets were made by stroking the lodestone with a piece of iron. When the lodestone was touched with a piece of iron the iron itself acquired the property of attracting other pieces of iron, or, as we now say, became magnetized. The time during which this property of attraction was retained depended upon the quality of the iron. If, upon removal from contact with the lodestone, the iron lost most of its magnetism, it was called a *temporary* magnet. A piece of steel which was hardened before magnetizing retained its magnetic properties indefinitely and accordingly was called a *permanent* magnet.

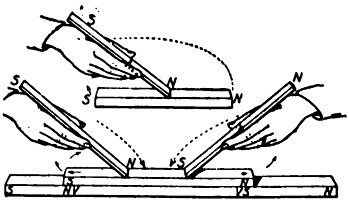


Fig. 3.

Magnets are now made either by stroking a permanent magnet in one direction by the piece of steel to be magnetized, **Fig.** 3, or by passing electric currents about the steel bar in a manner to be described later.

5. Magnet Poles.—The property of attracting iron, or the magnetism as it is called, is not uniformly distributed over the entire surface of a bar magnet, but it is concentrated at certain parts, usually the ends. These parts are called poles of the magnet, Fig. 4. When a bar magnet is suspended so as to swing

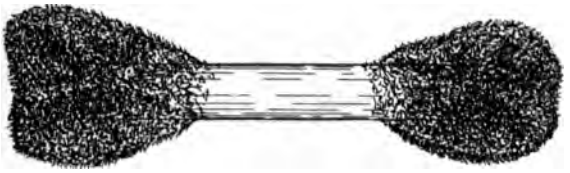
N  S

Fig. 4.

freely in a horizontal plane, it will be found that one end points in a northerly and the other end in a southerly direction, depending upon its position with reference to the earth. The end that points north is called the north-seeking, north, or positive pole, while the end that points south is called the south-seeking, south, or negative pole, Fig. 5. When two south-seeking poles, or two north-seeking poles of two magnets are brought near each other, the magnets tend to separate. When a north-seeking pole of

one magnet and a south-seeking pole of another magnet are brought near each other they attract. These facts are expressed by saying, *like magnet poles repel and unlike magnet poles attract each other.*

6. Unit Magnet Pole.—It is physically impossible to magnetize a piece of iron so as to produce only one pole. Neither is it possible to have all the magnetism concentrated at one point. Two long slim rods magnetized so that the polarity is confined to the ends may be used experimentally to determine the force between magnet poles.

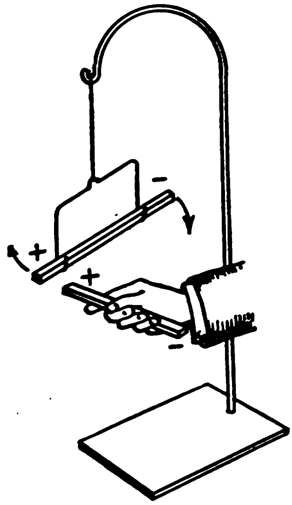


FIG. 5.

For purposes of mathematical analysis it is convenient to consider the magnetism to be concentrated at a point. A unit magnet pole is then defined as a *point pole which repels an equal point pole with a force of* 1 *dyne at a distance of* 1 *centimeter in a vacuum.* A dyne will be defined later.

When slim magnetized rods are used to determine experimentally the force between two poles, it is found that the force can be expressed by

$$F = \frac{mm'}{\mu d^2} \text{ dynes.}$$

Where m and m' are the pole strengths expressed in terms of unit magnet poles as defined above, d is the distance in centimeters between the poles, and μ is a quantity depending upon the medium in which the poles are immersed. If the experiment is performed in a vacuum, $\mu = 1$. This quantity μ is termed the permeability of the medium. The importance of this quantity will be explained more fully later.

7. Properties of Space Around a Magnet.—Although magnetic phenomena are associated with iron in some of its forms, it is not the iron as such that is of primary importance. The space surrounding the magnetized iron possesses important properties. If a sheet of paper be placed on a bar magnet and some iron filings be sifted upon the paper while in this position, it will be found that the iron filings, when the paper is tapped, arrange

themselves in curved lines as shown in Fig. 6. This clearly shows that the space around the bar magnet influences the iron filings. In fact, the iron filings become small magnets. The space or region which is capable of inducing magnetism in iron or other magnetic substances is called a *magnetic field.* The region or space around a bar magnet is thus a magnetic field, and its existence is made manifest by its influence on the iron filings. This representation of the magnetic field is only in one plane; that is, in the plane of the paper which is laid on the bar magnet. A similar design will be obtained if the bar magnet is turned on edge, or in any position parallel to its length. This shows that the magnetic field completely surrounds the bar magnet and is inseparably associated with it.

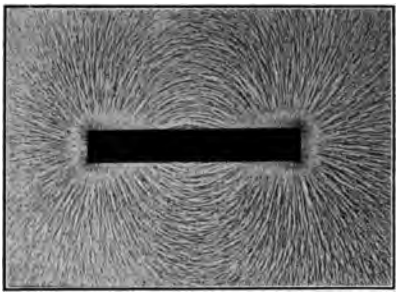


Fig. 6.

8. Unit Magnetic Field.—Just as the strength of a magnetic pole is measured by the force it exerts on a unit magnet pole, the strength of a magnetic field is defined in terms of the force it will exert upon a unit magnet pole. If a small compass be placed on the paper above the bar magnet, the magnetic needle will lie parallel or be tangent to the lines as shown in Fig. 7. The north pole of the compass needle is pulled in one direction and the south pole in the opposite direction. The magnetic field thus exerts a force upon the magnetic needle. If it were possible to isolate a north pole and place it on the paper it would, if free, move from the north pole of the bar magnet toward the south pole. The force that a magnetic field is capable of exerting upon a magnet pole, is used to define the field strength, a unit field being defined as follows:

A magnetic field of unit strength is one which is capable of exerting a force of 1 *dyne upon a unit magnet pole.* The unit of mag-

netic field strength or intensity is called the *gauss* after the famous German physicist and mathematician.

9. Conventional Representation of a Magnetic Field.—Since the iron filings are arranged in lines or rows, it is customary to speak of the magnetic field as consisting, or being composed, of lines, and the strength of field is then represented by the number of lines per square centimeter or per square inch, in a plane at right angles to these lines. A field of unit strength is then represented by 1 line per square centimeter, and a field of 10 units by 10 lines, etc. The student must remember, however, that this is merely a method of representing a magnetic field. The magnetic field occupies or permeates all of the space near and around a bar magnet. Usually the field is not of uniform strength

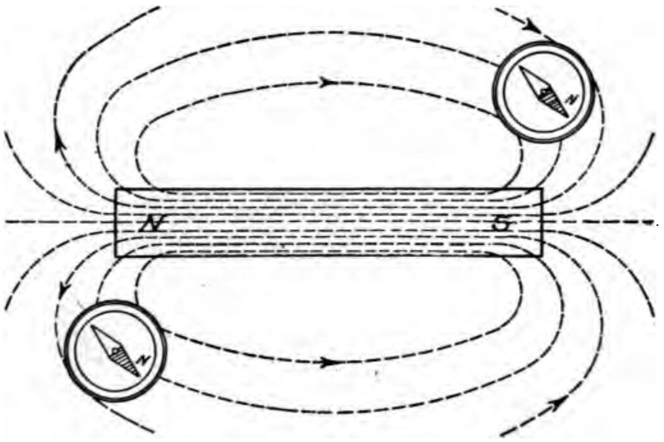


FIG. 7.

at every point, but there is no point in the space around the magnet entirely free from a magnetic field. The ether surrounding a bar magnet is not fibrous like a muscle; the system of lines is used merely for convenience in making calculations, and for the development of the electromagnetic theory. The magnetic lines are assumed to leave the north and to reënter the south pole of a magnet. The positive direction along the lines is from the north pole to the south pole, and this is said to be the direction of the field. This is indicated by arrow heads in Fig. 7. As the lines are curved, at any point in space the direction of the magnetic field will be the same as that of a geometrical line tangent to a magnetic line passing through the point.

A magnetic field is said to be uniform if at every point it has the same direction and intensity, Fig. 8. It is very evident from Fig. 6 that the magnetic field around a bar magnet is not uniform. The two important characteristics of a magnetic field are direction and intensity, or strength. As has already been pointed out, the strength of a magnetic field is measured by the force it is capable of exerting on a unit magnet pole. If a pole of strength m is placed in a magnetic field of strength H, the force exerted by the field on the pole, or rather the reaction between the two, is expressed by

$$F = mH.$$

There are different ways of experimentally determining m and H. These are explained in laboratory manuals.[1]

FIG. 8.

10. Number of Magnetic Lines Issuing from a Unit Magnet Pole.—Assume a unit magnet pole to be placed at the center of a sphere of 1 centimeter radius, Fig. 9. If an equal and like pole be placed anywhere on the surface of the sphere, it will be repelled by a force of 1 dyne. Thus, through every square centimeter of surface one magnetic line must issue. As the area of the surface is 4π square centimeters, it follows that 4π magnetic lines must issue from a unit magnet pole.

11. Magnetic Field between Magnet Poles.—Experiment shows that when like poles of two bar magnets are brought near each other, the magnets repel each other. The reaction between the magnetic fields near two like poles is well shown in Fig. 10. It is evident that the two magnetic fields push against each other, that is, there is a repulsion between them. On the other hand, when two unlike poles are brought near each other the fields coalesce or combine. The tension along the lines then tends to draw the poles together. This is shown in Fig. 11.

As the permeability of iron is quite high, a piece of iron placed

[1] See SMITH'S "Electrical Measurements."

in a magnetic field provides an easier path for the passage of the magnetic lines than the air. The magnetic lines will be crowded together within the iron, and the magnetic field in the vicinity of the iron will be distorted. This is shown by Fig. 12. This shows that iron offers less resistance to the passage of magnetic lines than does air, or that it is more permeable. It is this property which has given the quantity designated by μ its name. Substances whose permeability is greater than that of air are called *paramagnetic*, or merely *magnetic*. The magnetic lines, sometimes called lines of induction, are closed curves. Fig. 6 shows that they proceed from the north-seeking pole through space and reënter the iron bar at the south-seeking pole.

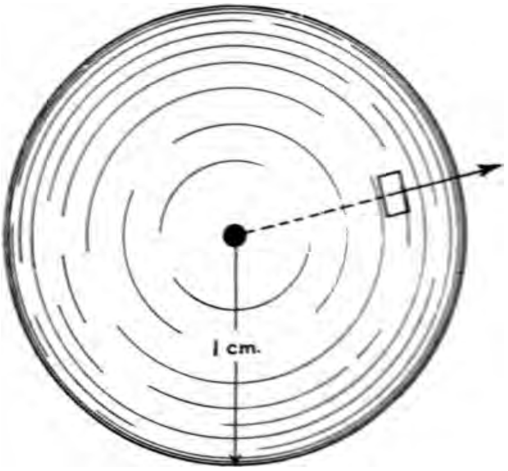


Fig. 9.

The lines of induction do not terminate at the poles, but are continuous throughout the iron. This is indicated in Fig. 7. The magnet proper may be considered as being composed of these lines. The north pole of the magnet is located at the surface where the lines emerge and the south pole where they enter.

The results of experiments suggested by Fig. 10 shows that a force of repulsion exists at right angles to the magnetic lines. When unlike poles are brought near each other as shown in Fig. 11, a force of attraction is manifest, or the magnetic lines have a tendency to contract. This is an important property of a magnetic field.

12. Magnetic Flux and Flux Density.—If at any point in a magnetic field, a plane be drawn at right angles to the direction of the magnetic lines the total number of lines cut by the plane is called the total flux of magnetic induction, or simply the magnetic flux. The total number of lines passing through 1 square

Fig. 10.

Fig. 11.

centimeter of the plane is the flux density at that point. When the magnetic field is uniform the flux density will be the same at any point in the plane. Under such conditions the total flux is given by

$$\Phi = BA, \qquad B = H\mu$$

Fig. 12.

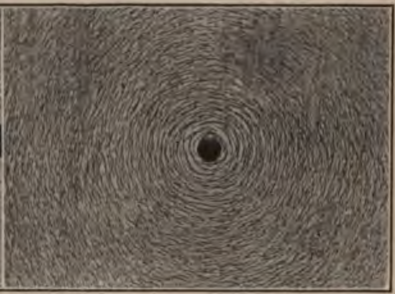


Fig. 13.]

where Φ represents the total flux,
B represents the flux density,
and A the area of the plane across which the flux passes.

When the field is not uniform, the flux density at different points will not be uniform. If the law of variation in the flux density is known, the total flux may be in many instances calculated by integral calculus.

13. Effect of Heat on a Magnet.—According to the molecular theory of magnetism, the development of magnetism is explained on the assumption that the particles of iron are turned under the influence of the magnetizing field. The iron molecules themselves become for the time being magnets, or magnetism is induced in the iron. At red heat, iron loses its magnetic quality. This means not only that a magnet may be demagnetized by being heated to about 800°C., but also that iron, when heated to this temperature, is no longer capable of being attracted by a magnet. On cooling, however, the iron regains its magnetic quality at a somewhat lower temperature.

According to the kinetic theory of matter all molecules are supposed to be in motion. This motion is greatly increased by heat; hence, heating a magnet will cause the molecules to move so rapidly that they can not be kept "lined up" by the influence of the magnetic field.

Recapitulation

1. *Magnetism* is that property a body has of attracting iron which is neither gravitation nor due to mechanical action of ordinary matter, and which will tend to set the body in a north and south direction. ✓

2. *Magnets* are bodies possessing the property of magnetism. Permanent magnets are usually made of hardened steel and retain their magnetism indefinitely. Temporary magnets are usually made of soft iron. They retain their magnetism only so long as the magnetizing influence is present.

3. The poles of a magnet are the points or surfaces on which the magnetism is manifest.

4. The laws of magnetic attraction and repulsion are: (*a*) Like poles repel and unlike poles attract each other; (*b*) the forces of attraction or repulsion are directly proportional to the product of the pole strengths and inversely to the product of the permeability by the square of the distance between them.

5. The *strength of a magnet pole* is measured by the force the magnet pole exerts upon a unit magnet pole. Unit pole strength or a unit pole is that pole strength which repels an equal and like pole at a distance of 1 centimeter in a vacuum (or air) with a force of 1 dyne. There are 4π magnetic lines emanating from a unit magnet pole.

6. A *magnetic field* is the region or space about a magnet which is permeated by a magnetic influence.

7. A *unit magnetic field* is one which is capable of exerting a force of 1 dyne on a unit magnet pole.

8. The *strength of a magnetic field* is usually represented graphically by the number of lines per square centimeter in a plane at right angles to direction of the field.

9. The *flux density* is the number of magnetic lines in a square centimeter

of a plane perpendicular to the direction of the magnetic field. It is represented by the letter B.

10. The *total flux* is the total number of magnetic lines in a magnetic field. It is represented by the symbol Φ. For a uniform magnetic field $\Phi = BA$.

11. When heated, iron loses its property of magnetism and ceases to be magnetic at about 800°C.

CHAPTER II

ELECTROMAGNETISM

14. Magnetic Field Around a Current-carrying Wire.—When a current-carrying wire is placed either above, or below, and parallel to a magnetic needle, the needle will be deflected from its normal position. This fact was first observed by Oersted. Ampere explained this phenomenon by saying that a current-bearing wire is surrounded by a magnetic field, and that the interaction of this field with the magnetic field of the compass needle caused the latter to be deflected. The direction of the magnetic lines around a wire can be shown by passing a wire vertically through a horizontal sheet of paper and while the current is passing, sprinkling iron filings on the paper. When this is done the iron filings will arrange themselves as shown in Fig. 13. The black spot in the center is the cross-section of the wire.

The direction of deflection of a magnetic needle when in the vicinity of a current-carrying wire is determined by the relative position of the two and the direction of current flow. This shows that the magnetic lines around the wire have definite directions. Fig. 13 shows that the magnetic lines are circles having their centers coincident with that of the wire. It is found that when the wire is held above and parallel to the magnetic needle, the north-seeking pole of the needle is deflected to the west when the current is flowing north, and when the direction of current is reversed the north-seeking end is deflected toward the east. Thus the lines have an opposite effect when the current is reversed. This is explained by saying that the direction of the lines of the magnetic field is determined by the direction of the current producing them. The relative direction of current and magnetic lines is conventionally assumed to be in a clockwise direction when viewed along the wire in the direction of current flow. This is in harmony with the assumed direction of the magnetic lines around a magnet.

Many rules have been given for remembering the relative direction of current flow and resulting magnetic lines, the fol-

lowing is, however, as simple as any: *Grasp the wire with the right hand with the thumb extended along the wire in the direction of current flow; the fingers will then point in the direction of the magnetic lines encircling the wire.* This rule is illustrated by Fig. 14.

15. Solenoid.—A helical coil of insulated wire is called a solenoid. When a current of electricity flows through the convolutions of a solenoid, the solenoid has many of the properties of a bar magnet. The two ends are of different polarity and if the solenoid be suspended so as to swing freely with its axis in a horizontal plane it will assume a position in the magnetic meridian.

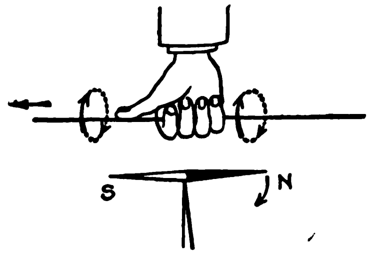


FIG. 14.

Since the direction of the magnetic lines around a current-carrying wire is determined by the direction of current flow it is evident that when the wire is coiled, the magnetic lines must enter at one end and leave at the other end of the solenoid. This is shown in Fig. 15. It will be noticed that all of the lines do not go the full length of the coil, but that many pass out between

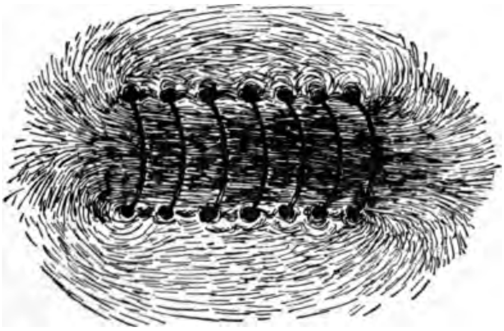


FIG. 15.

the convolutions. The magnetic field is not uniform throughout the length of the solenoid, but grows weaker from the center toward the ends. The end from which the lines emerge is the north-seeking pole, while the other end is the south-seeking pole. The polarity of the solenoid can readily be determined by the rule for determining the direction of the magnetic lines about

a straight conductor. For, if one of the convolutions or turns of wire be grasped by the right hand, as directed in the rule, the fingers extending along the axis of the solenoid will point toward the north-seeking pole of the solenoid; or grasp the solenoid with the right hand with the fingers curved around the solenoid in the direction of current flow, the extended thumb will then point toward the north-seeking pole. The same relation can, however, be expressed as follows: *If an observer face one end of a solenoid and the current flows in a counter-clockwise direction, the north-seeking pole of the solenoid is nearer the observer. If the current flows in a clockwise direction, the south-seeking pole is nearer the observer.* Solenoids and coils are of great importance in all electrical machinery.

16. Strength of the Magnetic Field Around a Current-carrying Wire.—The magnetic field around a straight current-carrying

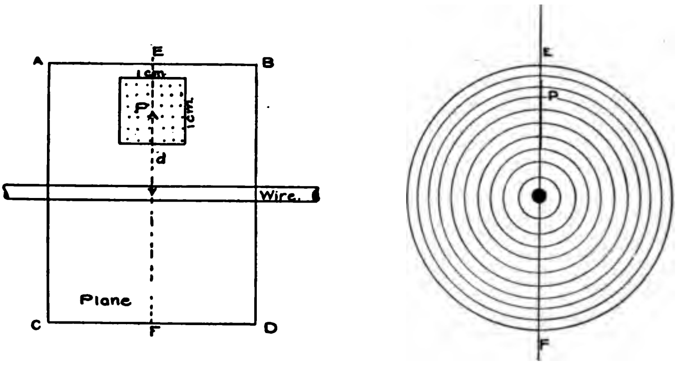


FIG. 16.

wire is composed of concentric lines wrapped around the wire. The strength of the field at any point will then be represented by the number of lines per square centimeter of a plane containing the wire, Fig. 16. The density, or number of lines per square centimeter, decreases from the wire outward. Experiments, as well as theory, show that the strength at a point in space of a magnetic field due to a current depends directly upon the current strength and inversely upon the distance of the point from the wire. In algebraic symbols, if H represents the field strength at the point P, I the current in absolute units, and d the distance of the point from the current-carrying wire, then,

$$H = \frac{2I}{d}.$$

17. Reaction between Current-carrying Wires.—When two current-bearing wires are brought near each other, they will be either attracted or repelled if parallel, and if not parallel, will tend to become parallel. The force of attraction or repulsion is due to the interaction of the magnetic fields around the wires. The manner in which such a force develops will be readily understood from Figs. 17 and 18. When the two wires are parallel and the

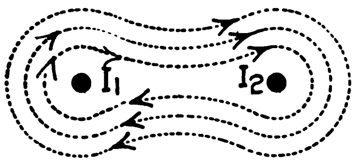


FIG. 17.

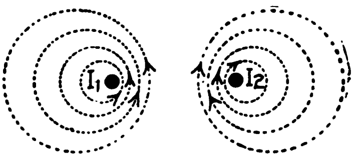


FIG. 18.

current flows in the same direction, the magnetic lines will coalesce and encircle both wires. The tension along the magnetic lines will then tend to draw the wires together. This is represented by Fig. 17.

When the currents flow in opposite directions, the magnetic lines can not combine as they are oppositely directed. The

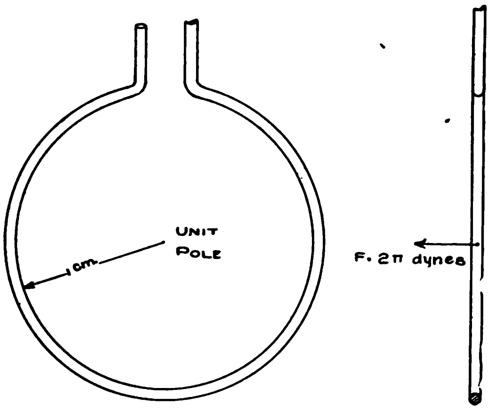


FIG. 19.

reaction between the fields will push the wires farther apart. These conditions are represented by Fig. 18. The force of attraction or repulsion is proportional to the product of the currents in the two conductors so long as the conductors maintain the same relative position.

18. Magnetic Field at the Center of an Annular Coil.—When a wire along which an electric current is flowing is bent into a ring,

all of the magnetic lines due to the current will pass through the ring, Fig. 19. The definition of the electromagnetic unit of current is based on this fact. The *absolute ampere* is defined as the current which will exert a force of 2π dynes upon a unit magnet pole placed at the center of a circular coil of 1 turn of wire, of 1 centimeter radius, of which the current-carrying wire is the circumference. The magnetic-field strength, which is measured by the force exerted on a unit magnet pole, produced by a unit current at the center of a circular coil of 1 centimeter radius, is $2\pi N$, where N is the number of turns on the coil. As the strength of the magnetic field varies directly as the current and inversely as the radius, the magnetic-field strength at the center of an annular coil, Fig. 20, must be

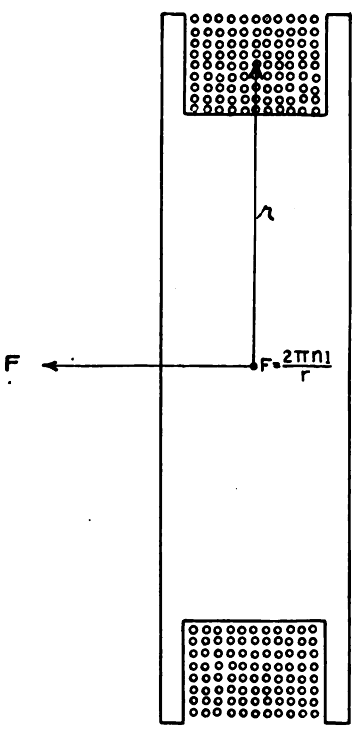


FIG. 20.

$$H = \frac{2\pi NI}{r} \text{ gausses,}$$

where N is the number of turns on the coil,
I is the current in absolute units,
and r is the mean radius of the coil in centimeters.

An ampere is one-tenth of the absolute unit of current.

19. Force Exerted by a Magnetic Field upon a Current-carrying Wire.—The operation of electric motors is due to the interactions between the magnetic field associated with a magnet and that of a current-carrying wire. A knowledge of the value and direction of this force is thus important. It has just been shown that the force exerted by a current flowing in a circular coil of one turn on a unit pole at its center is $\frac{2\pi I}{r}$ dynes. This force is at right angles to the plane of the coil. As action is equal to reaction, it is evident that the force on the coil must be

equal and opposite. This force is due to the flux at the wire. The flux density at the wire must be equal to the total flux issuing from a unit magnet pole (4π) divided by the area of the surface of the sphere r centimeters radius. This is $4\pi r^2$. Hence

B at the wire is $-\dfrac{4\pi}{4\pi r^2} = \dfrac{1}{r^2}$ lines per square centimeter.

$$\text{The force } F = \frac{2\pi I}{r} \text{ dynes,}$$

and

$$\frac{F}{B} = \frac{2\pi I}{r} \times r^2 = 2\pi r I$$

$=$ circumference of circle times the current.

Then $F = BlI$ dynes, where $l = 2\pi r$ or the length of wire in the magnetic field.

20. Electromagnets.—A current-bearing solenoid has the properties of a bar magnet. It would, however, require enor-

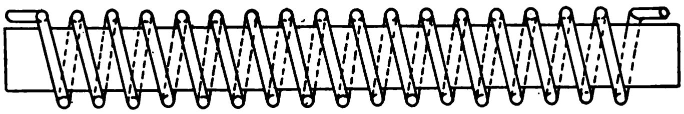


FIG. 21.

mous currents to make very strong magnets so long as the solenoid had only an air core. It is the combination of a solenoid and an iron core that makes possible the development of strong magnetic fields. Such a combination is called an electromagnet, Fig. 21.

When a current of a given value is sent through the convolutions of the solenoid, magnetic poles are developed at the ends of the solenoid in accordance with the principles already explained. If while the current is flowing, an iron rod be inserted into the solenoid it will be found that the electromagnet becomes a much stronger magnet. The iron has thus a property of greatly increasing the number of magnetic lines. Perhaps a better way of explaining the action of the iron is to say that it offers a much smaller resistance to the passage of the magnetic lines, and accordingly the same current will send many more lines through the iron than through the air alone.

If the magnetic circuit is composed wholly of iron, the opposi-

tion to the building up of a magnetic field is much less than when the circuit is part iron and part air. Under such conditions the same current will develop an even stronger magnetic field. Thus, an electromagnet in which the magnetic circuit contains only a small air gap is more effective than one in which the air gap is large, Fig. 22.

21. Magnetic Field Inside of an Anchor Ring.—Suppose a long helical coil of wire is bent into a ring, Fig. 23. When a current is passed through the wire of such a solenoid, the magnetic field is confined to the interior of the spiral ring and in the direction

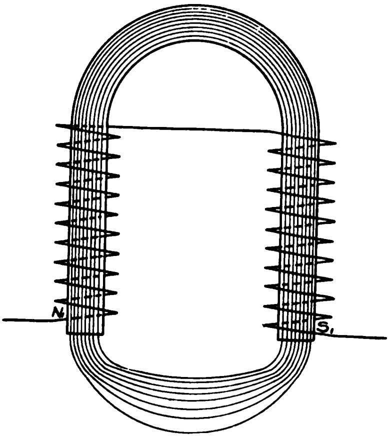


FIG. 22.

of its length. The work required to move a unit magnet pole around the magnetic circuit, that is, length of the ring, can readily be calculated. A straight conductor is surrounded by a magnetic field whose strength at any point is $\frac{2I}{d}$. When a unit magnet pole is moved around the wire at a distance d against the magnetic field the numerical value of the work done will be

$$2\pi d \times \frac{2I}{d} = 4\pi I.$$

If a unit magnet pole is moved along the circular axis of the anchor ring of N turns one complete revolution, it will have made one complete turn around each turn of wire. The total work will then be N times the work done in moving the unit pole around one conductor. Hence the work done in moving the magnet pole

one complete revolution along the circular axis of the coil is

$$W = 4\pi NI.$$

If H is the force exerted by the magnetic field on a unit magnet pole within the anchor ring, then by definition $W = Hl$, where l is the length of the path along which the magnet pole was moved. Equating these expressions for W we have

$$Hl = 4\pi NI,$$

and

$$H = \frac{4\pi NI}{l},$$

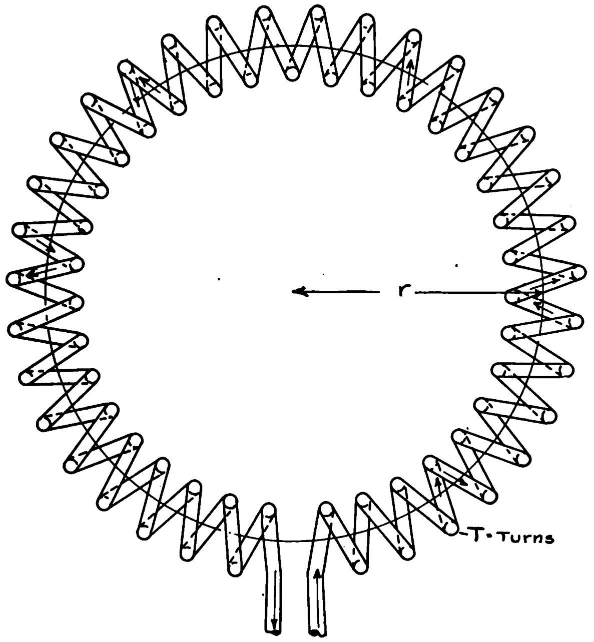


FIG. 23.

where H is numerically equal to the strength of the magnetic field inside of the anchor-ring solenoid. If I is measured in amperes, then

$$H = \frac{4}{10}\frac{\pi NI}{l}.$$

If r is the radius of the path, then $l = 2\pi r$, which when substituted for l gives

$$H = \frac{NI}{5r}.$$

This shows that the intensity of the field is not constant across the section of the ring, but varies inversely as r, the radius of the ring.

22. Magnetic Field Inside of a Long Straight Solenoid.—It is evident that if the radius of the anchor ring is increased greatly a part of the anchor ring will approach a straight solenoid. A long straight solenoid may be considered as a portion of an anchor ring with an infinite radius. The magnetic field near the center of a long solenoid will be the same as in the anchor ring, viz.,

$$H = \frac{4\pi NI}{10l}$$

$$= \frac{1.257NI}{l} \text{ gilberts per centimeter.}$$

A more accurate expression for the field intensity inside of any solenoid is

$$H = 1.257NI \left[1 - \frac{r^2}{4(l-x)^2} - \frac{r^2}{4x^2} \right],$$

where l = length of solenoid,
x = distance of point inside of the solenoid from one end,
$l - x$ = distance of the point from the other end,
r = radius of the solenoid.

23. Magnetomotive Force, and Magnetizing Force of a Solenoid.—The magnetomotive force is defined as numerically equal to the work expended in moving a positive unit magnet pole around the magnetic circuit against the magnetic field. It has been shown that this, in both the anchor ring and long solenoid, is

$$\text{m.m.f.} = Hl = 1.257NI \text{ gilberts,}$$

when I is in amperes. H, the magnetizing force of the solenoid, is equal to the magnetomotive force per unit length. The student should remember, however, that neither the magnetomotive force nor the magnetizing force is of the physical nature of a force. They are of the nature of work per unit magnet pole.

If an iron core be inserted into the anchor ring or solenoid, the flux density B is μH, where μ = permeability. Then

$$B = \frac{1.257NI\mu}{l}.$$

The total flux

$$\Phi = BA = \frac{1.257NI}{\frac{l}{\mu A}}$$

$$= \frac{\text{m.m.f.}}{\frac{l}{\mu A}}.$$

The quantity $\frac{l}{\mu A}$ is called the reluctance, $\mathcal{R}$. We may then write

$$\Phi = \frac{\text{magnetomotive force}}{\text{reluctance}}$$

$$\Phi = \frac{1.257NI}{\mathcal{R}} \text{ maxwells.}$$

This equation for magnetic flux is analogous to the mathematical expression of Ohm's law. The magnetomotive force is analogous to electromotive force, and reluctance is analogous to resistance. As the reluctance $\mathcal{R} = \frac{l}{\mu A}$ it is evident that the reluctance of a magnetic circuit varies directly as the length and inversely as the product of the permeability by the cross-sectional area of the circuit. μ for air is practically unity.

If a magnetic circuit consists of several parts in series, each having a different length, cross-section, and permeability, the total reluctance is the sum of the reluctances of the several parts.

Thus, if $l_1, A_1, \mu_1,$
$l_2, A_2, \mu_2,$
and l_3, A_3, μ_3 are the lengths, cross-sectional areas, and permeabilities of three parts respectively, the total reluctance is

$$\mathcal{R} = \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_3}{\mu_3 A_3},$$

and if a magnetomotive force of $1.257NI$ units is applied, the flux resulting is

$$\Phi = \frac{1.257NI}{\frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_3}{\mu_3 A_3}}$$

$$= \frac{\text{m.m.f.}}{\mathcal{R}}.$$

24. Magnetic Properties of Bodies.—Many investigations upon the magnetic properties of substances have been made. Why

some bodies are magnetic while others are not is at present unknown. We only know that some substances can be magnetized, and we know the properties of these substances under different degrees of magnetization. With reference to their magnetic properties, substances are divided into three classes or groups: ferromagnetic, paramagnetic, and diamagnetic.

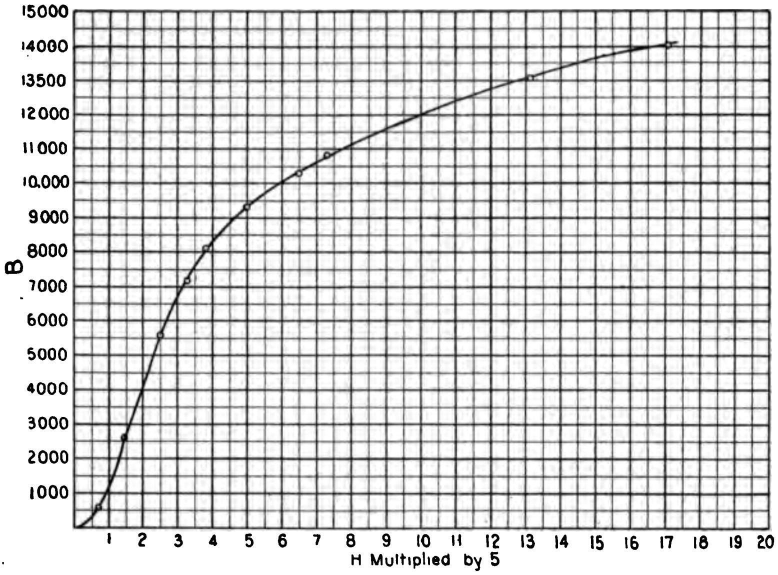
(a) *Ferromagnetic substances* are those whose intensity of magnetization at saturation is of the same order of magnitude as that of iron. To this class belong iron, nickel, cobalt, magnetite, pyrrhotite, and the alloys of copper, manganese, and aluminum commonly known as Heusler alloys. The permeability of ferromagnetic substances is relatively large.

(b) *Paramagnetic substances* are those which when subjected to the influence of a magnetic field become magnetized in the direction of the field but the resulting magnetization is very weak. Paramagnetic substances are oxygen, nitrogen dioxide, palladium, platinum, manganese, and the salts of some metals. The permeability of paramagnetic substances is greater than unity, but not very large.

(c) *Diamagnetic substances* are those which when subjected to the influence of a magnetic field become magnetized in a direction opposite to that of the field. The resulting magnetization is also very feeble. Bismuth is a good example of a diamagnetic substance. The permeability of diamagnetic substances is less than unity.

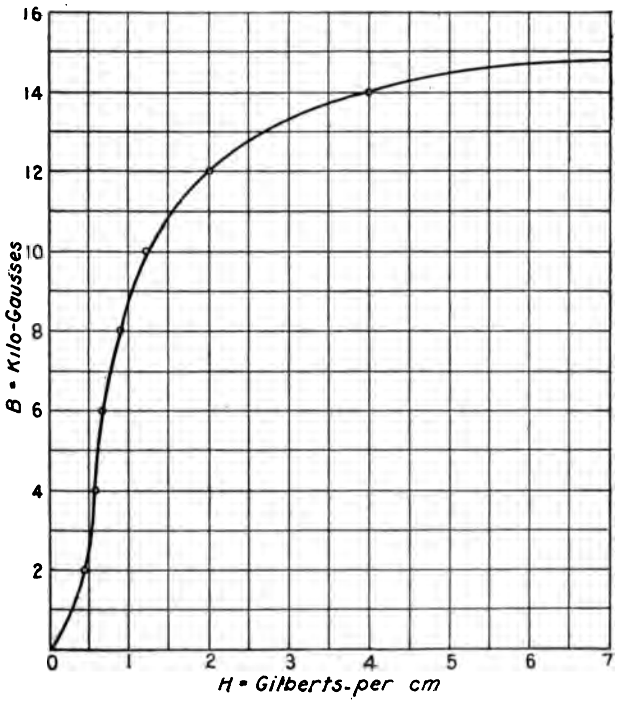
Some bodies, such as iron, when heated show a gradual transition from the ferromagnetic to the paramagnetic state or *vice versa*, but as yet no substance, with the exception of tin, has been found which by a change of the physical conditions, will pass from the diamagnetic to the paramagnetic state.

25. Magnetic Properties of Iron.—As iron in some form enters into all electrical machinery, its magnetic properties are of great importance. When a sample of iron is subjected to the influence of a magnetic field it becomes magnetized. The relation between the flux density B and the strength of the magnetizing force H, producing the flux density, is usually shown by means of a magnetization curve commonly called B–H curve. A B–H curve for an iron ring is shown in Fig. 24, and a similar curve for a standard rod of iron is shown in Fig. 25. An examination of this curve shows that for values of H below 0.5 gilbert per centimeter the flux density increases very slowly. As the strength of



15000
14000
13500
12000
11000
10.000
9000
8000
7000
6000
5000
4000
3000
2000
1000
B
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
H Multiplied by 5

FIG. 24.



16
14
12
10
8
6
4
2
B • Kilo-Gausses
0 1 2 3 4 5 6 7
H • Gilberts-per cm

FIG. 25.

H increases from 0.5 to 2 gilberts the flux density increases rapidly from about 2,000 to 12,000 lines per square centimeter. For higher values of H the flux density again increases at a much slower rate. This is a typical B–H curve for iron. The absolute values of B for corresponding values of H will be different for different samples of iron, but the general form in every

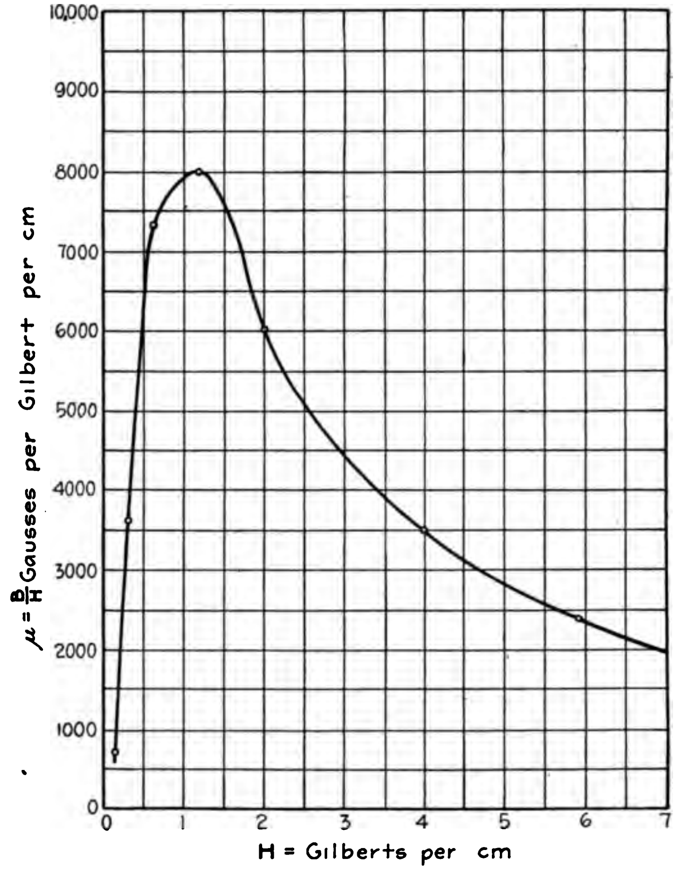


FIG. 26.

case will be the same. Such curves are of extreme importance in the design of electrical machinery. The μ–H, or permeability, curve, Fig. 26, is easily obtained from the B–H curve. The value of μ at any value of H is obtained by dividing the value of B by the corresponding value of H. Thus when $B = 10,000$, $H = 1.25$ and accordingly $\mu = 10,000 \div 1.25 = 8,000$. Other

values of μ are calculated in the same way, and from these the μ–H curve is plotted. This curve shows that the permeability of iron is not a constant quantity. This is an important fact. The sharp bend of the B–H curve, in this case that portion of the curve between B = 10,000 to B = 12,000, is known as the

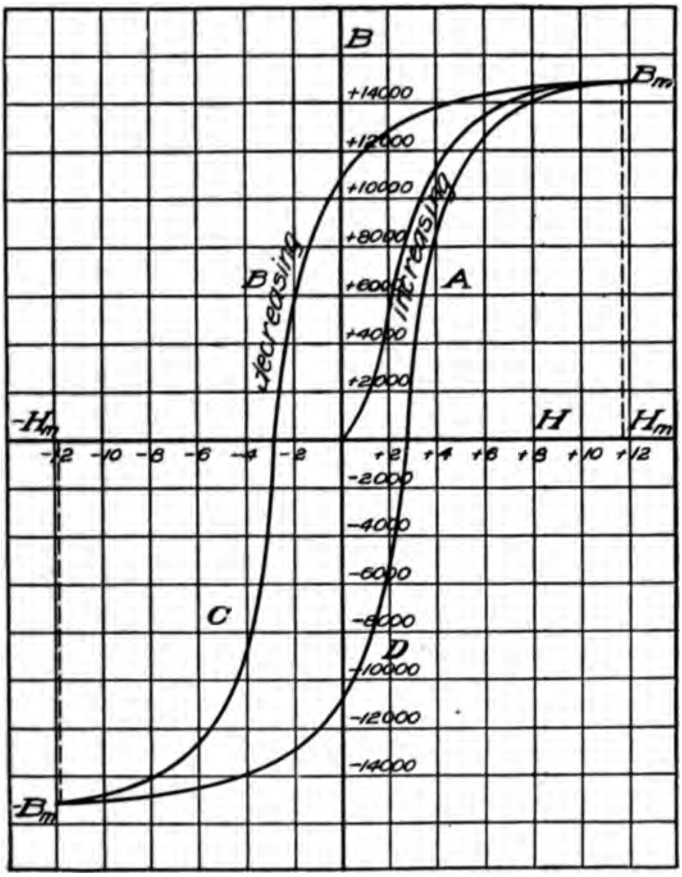


FIG. 27.

knee of the curve. For practical purposes, this is the point of saturation of the iron.

Fig. 25 shows that as the magnetizing force increases, the flux density increases, although not uniformly.

26. Hysteresis.—When a sample of iron is subjected to the influence of a magnetizing force which can be increased by steps

and the magnetizing force and flux density are plotted, curve, Fig. 25, results. If the magnetizing force be increased to any value, such as 4 gilberts, the flux density will reach a corresponding value of 14,000. If now the magnetizing force be decreased step by step the flux density will not decrease along the magnetization curve, but will remain higher. This is illustrated by Fig. 27. This figure shows that when the magnetizing force has been reduced to zero, the flux density is still about 10,800 lines per square centimeter. This value is called *remanent* or *residual* magnetism. The flux density drops to zero only after the magnetizing force has been reversed and, in the illustration shown, increased to about 3 gilberts per centimeter in the negative direction. The magnetizing force required to reduce the residual magnetism to zero is called *coercive* force. It is thus evident that work must be done in causing the molecules to turn around and point in the opposite direction. The decreasing values of the flux density are higher than the increasing values of the flux density corresponding to the same magnetizing force. This lagging behind has, therefore, been given the name *hysteresis* which means "lagging behind," and the area bounded by the four lines A, B, C, and D is called a *hysteresis loop*. This loop is due to the fact that some work must be done in magnetizing the iron first in one direction and then in the other direction. The wider the loop the greater the amount of energy spent in the process of reversing the magnetization. This energy appears as heat in the iron, and is lost for all practical purposes. For electrical machines in which the magnetization is variable, or alternates, it is of great importance to use iron whose hysteresis loop is very narrow and consequently has small hysteresis loss. Hysteresis loops give valuable information in regard to the magnetic qualities of iron.

Recapitulation

1. Every current-carrying wire is surrounded by a magnetic field which is produced by the current. The direction of this magnetic field is determined by the following rule:

RULE.—*Grasp the wire with the right hand, with the thumb extended along the wire in the direction of current flow; the fingers will then point in the direction of the magnetic lines encircling the wire.*

2. A *solenoid* is a helical coil of insulated wire. The magnetic properties of a current-carrying solenoid are much the same as those of a bar magnet.

3. The intensity of a magnetic field at a point in space at a distance of d centimeters from a straight wire carrying a current of I abamperes is

$$H = \frac{2I}{d} \text{ gausses}$$

$$\doteq \frac{0.079I}{d} \text{ gausses,}$$

when I is in amperes and d in inches.

4. When the currents flow in the same direction in two parallel conductors a force of attraction will exist between the conductors.

When the currents flow in opposite directions, a force of repulsion will exist between the conductors.

5. The absolute unit of electric current is a current of such strength which when flowing in a conductor bent into a ring of 1 turn, 1 centimeter in radius, will exert a force of 2π dynes on a unit magnet pole placed at the center of the ring.

When a current of I abamperes flows through a ring of N turns and r centimeters radius, the field intensity at the center of the ring is

$$H = \frac{2\pi NI}{r}$$

$$= \frac{0.247NI}{r},$$

when I is in amperes and r in inches.

6. The force exerted by a magnetic field whose flux density is B lines per square centimeter upon a conductor l centimeters long carrying a current of I absolute units is

$$\begin{aligned} F &= BlI \text{ dynes} \\ &= 8.85BlI \times 10^{-8} \text{ pounds,} \end{aligned}$$

when B is flux density per square inch, l is in inches, and I is in amperes.

7. An electromagnet consists of an iron core within a solenoid magnetized by an electric current flowing in the solenoid.

8. The intensity of the magnetic field within an anchor ring of l centimeters length and N turns when a current of I absolute units is flowing through the turns on the ring is

$$H = \frac{4\pi NI}{l} \text{ gausses}$$

$$= \frac{1.257NI}{l} \text{ gausses,}$$

when I is in amperes and l in centimeters, or

$$H = \frac{0.495NI}{l} \text{ gausses,}$$

when I is in amperes and l is in inches.

The mathematical relation between the flux density B in lines per square

centimeter, the intensity of the magnetic field $\dot{H}$ in gausses, and the magnetic permeability μ is

$$B = \mu H$$

$$= \frac{1.257NI\mu}{l} \text{ gausses,}$$

when I is in amperes and l is in centimeters, or

$$B = \frac{3.19NI\mu}{l} \text{ gausses,}$$

when B is in lines per square inch, I is in amperes, and l is in inches.

9. Magnetomotive force is defined as the difference of magnetic potential along a line of magnetic intensity from any point in the field, back to the same point. It is measured by the work done in moving a unit magnet pole around the circuit against the magnetic field. The magnetomotive force of a solenoid is given by the expression

$$\text{m.m.f.} = 4\pi NI \text{ gilberts}$$
$$= 1.257NI \text{ gilberts,}$$

when I is in amperes.

10. The magnetizing force of a coil or solenoid is the magnetomotive force per unit length of solenoid. It is expressed by

$$H = \frac{4\pi NI}{l} \text{ gilberts per centimeter}$$

$$= \frac{1.257NI}{l} \text{ gilberts per centimeter,}$$

when I is in amperes and l is in centimeters, or

$$H = \frac{0.495NI}{l} \text{ gilberts per inch,}$$

when I is in amperes and l is in inches.

11. The reluctance, $\mathcal{R}$, of a magnetic circuit is a property of the circuit which depends upon the length, cross-section, and permeability of the circuit. It is analogous to resistance in the electric circuit. The algebraic expression for reluctance is

$$\mathcal{R} = \frac{l}{\mu A}.$$

Unit reluctance is that reluctance in which a flux of 1 maxwell is produced by a magnetomotive force of 1 gilbert. The unit of reluctance is called the oersted.

12. The relation between magnetomotive force, reluctance, and flux is given by

$$\text{Flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}.$$

$$\Phi = \frac{\text{m.m.f.}}{\mathcal{R}}.$$

13. Permeability of a substance is a property which modifies the interaction of magnetic poles when immersed in or separated by this substance. In order to evaluate this constant, the force between two poles is taken as inversely proportional to the permeability,

$$F = \frac{m_1 m_2}{\mu d^2}.$$

14. Ferromagnetic substances are substances whose permeability is very high.

15. Paramagnetic substances are substances whose permeability is larger than unity but low.

16. Diamagnetic substances are those whose permeability is less than unity.

17. A hysteresis curve is a curve representing the flux density as a function of the magnetizing force when the latter is carried through a complete cycle between equal positive and negative values.

CHAPTER III

ELECTROMAGNETIC INDUCTION

27. Introduction.—In the preceding chapter it has been shown that when a current of electricity flows along a wire, the wire is surrounded by a magnetic field. In other words, the flow of electricity produces a condition in the ether surrounding the wire, which we call magnetic. The question naturally arises, if the flow of electricity along a wire produces a strained or magnetic condition in the ether surrounding the wire, will a current of electricity be produced in the wire if it is suddenly plunged into a magnetic field. That is, if some other means are used to produce the same condition around the wire will this result in a current of electricity in the wire. A complete answer to this question can be obtained only by experiment.

28. Electromagnetic Induction.—Faraday showed that when a wire cuts across a magnetic field, or when a magnetic field is

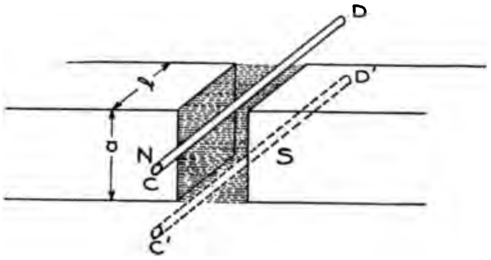


FIG. 28.

suddenly built up around the wire, an electric current will flow if the wire forms a closed coil. When the coil is open, of course no current can flow, but an electromotive force is induced nevertheless. Thus it is preferable to say that whenever a wire cuts across a magnetic field or when a magnetic field is suddenly built up around a wire, an electromotive force is induced in the wire. The significance of Faraday's experiments will be more easily understood from a consideration of Fig. 28. In this figure two opposite magnetic poles are shown near each other. Between them is the magnetic flux Φ which we shall assume as

being cut by the conductor CD moving downward. If the conductor starts from the position CD and moves to the position $C'D'$ it will cut across the flux Φ. A galvanometer or other sensitive current detecting device connected to the ends of the conductor will show that during the motion of the conductor from CD to $C'D'$ an electromotive force is induced, that is, a current flows through the galvanometer. Experiment thus answers the question in the affirmative, and it remains to consider the relation between the rate of cutting and the induced electromotive force.

29. Value of Induced Electromotive Force.—It is found by experiment that when the intensity of the magnetic field remains constant and the speed of the conductor is varied, the electromotive force is directly proportional to the speed; when the magnetic field between the two poles is changed, and the conductor

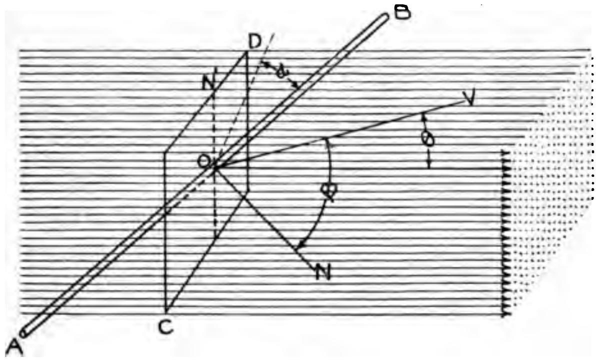


FIG. 29.

is moved at the same speed, it is found that the induced electromotive force has changed in the same ratio as the magnetic field. Furthermore, if the conductor is moved endwise, from C toward D no electromotive force whatever is induced. If the width l of the magnetic poles is reduced, the electromotive force induced by relative motion of conductor and field is reduced in direct ratio to the reduction in the width of the magnetic field through which the conductor is moved. In Fig. 28 the conductor is assumed to move at right angles to the magnetic lines. When the conductor moves in a direction making an angle θ with the direction of the lines, the electromotive force induced is found to be proportional to the component of the speed normal to the lines, or to sin θ, and finally if the conductor is moved in a direc-

tion other than in a line perpendicular to its length, the resulting electromotive force is proportional to the component of its speed in a direction normal to its length. These experimental facts can be expressed mathematically as follows:

Let a magnetic field be represented by horizontal straight lines, Fig. 29. Let the conductor AB make an angle α with the plane CD normal to the magnetic field and let its direction of motion be indicated by the vector OV which makes an angle β with the perpendicular to the conductor, and an angle θ with the direction of the magnetic lines. Furthermore, let V be the velocity of the conductor in the direction OV. The speed in the direction ON, normal to the conductor is $V \cos \beta$, and the component of this in the direction ON' is $V \cos \beta \sin \theta$. The induced electromotive force is also proportional to the component of the conductor normal to the field. If l represents the length of conductor immersed in the field, and this makes an angle α with the normal to the field, the component in a plane normal to the field is $l \cos \alpha$. Experiment also shows that when a conductor moves across a magnetic field the induced electromotive force is proportional to the flux density, or strength of the magnetic field. Let B represent this flux density. We thus have

$$E \propto V \cos \beta \sin \theta,$$
$$E \propto l \cos \alpha,$$
and
$$E \propto B,$$

when E and B are measured in absolute units.

Hence $E = BlV \cos \beta \sin \theta \cos \alpha$.

But $lV \cos \beta \sin \theta \cos \alpha$ is the projection of the area, traced by the conductor of length l in unit time, upon the normal plane. If we represent this area by A we have

$$E = BA.$$

But $BA = \Phi =$ flux crossed by conductor in unit time. If the flux distribution is uniform and if Φ is the flux cut in t seconds, then $E = \frac{\Phi}{t}$.

The general principles of electromagnetic induction have been summarized by Steinmetz as follows:

"If an electric conductor moves relatively to a magnetic field, an electromotive force is induced in the conductor, which is proportional to the intensity of the magnetic field, to the length of the conductor, and to

the speed of its motion perpendicular to the magnetic field and the direction of the conductor."

It is worth while to point out that the magnetic lines must be actually cut by the conductor before an electromotive force will be induced. The conductor must move across the lines, and it is immaterial whether the magnetic field is stationary and the conductor moves, or the conductor is stationary and the magnetic field moves across it, or is suddenly built up around the conductor. The relative motion will result in an electromotive force being produced in the wire.

In order that the student may get a clear understanding of the principles of operation of electrical machinery, one must realize that the magnetic field surrounding a magnet is the seat of the energy that causes a current to flow in the wire or coil being moved across the field.

The magnetic lines have certain propertics which are of interest. They are always closed curves; they behave like tightly stretched rubber bands; they tend always to contract; they never intersect; and they repel one another laterally.

A knowledge of these properties together with the properties of the magnetic field surrounding a current-carrying wire aids in understanding the phenomena resulting when a portion of a closed conductor in which no current is flowing is moved across the lines of a uniform magnetic field.

The expression, $E = \frac{\Phi}{t}$, gives the average pressure induced in one conductor when it cuts across a flux Φ in t seconds. If n conductors cut across the same flux, it follows that the pressure induced in each will have the same value. When these conductors are connected, as in a coil, so that the individual pressures are added and in the same direction, the average pressure for the n conductors is

$$E = \frac{n\Phi}{t}.$$

The value of the induced pressure is proportional to the rate of cutting of magnetic flux.

The practical unit of pressure is the *volt,* which is the pressure generated when the conductor is cutting the flux at the rate of 10^8 or 100,000,000 lines per second. The pressure generated in a circuit is dependent on this rate of cutting of magnetic lines.

It may be due to a single conductor cutting 10^8 lines per second or a large number of conductors, properly connected, each cutting a correspondingly reduced number of magnetic, or better lines of induction.

To change absolute units of pressure to volts we divied by 10^8, hence

$$E = \frac{n\Phi}{t \times 10^8} \text{ volts.}$$

Illustrative Examples

1. The dimensions of the pole faces in Fig. 28 are 20 by 40 centimeters· If the flux density B is 5,000 lines per square centimeter and the conductor moves across this fiux in ½ second, what is the average value of the induced pressure?

Solution.—

$$\begin{aligned} E &= \frac{\Phi}{t \times 10^8} \text{ volts} \\ \Phi &= B \times A \\ &= 5{,}000 \times 20 \times 40 \\ &= 4{,}000{,}000 \text{ maxwells,} \end{aligned}$$

then

$$\begin{aligned} E &= \frac{4{,}000{,}000}{\frac{1}{2} \times 10^8} \\ &= 0.08 \text{ volt for one conductor.} \end{aligned}$$

2. Suppose one side of a coil of 1,000 turns cuts the flux specified in example 1, in 0.1 second, what will be the pressure between the terminals of the coil?

Solution.—

$$\begin{aligned} E &= n\frac{\Phi}{t \times 10^8} \text{ volts} \\ \Phi &= 4{,}000{,}000 \\ n &= 1{,}000 \\ t &= 0.1 \text{ sec.} \end{aligned}$$

Hence,

$$\begin{aligned} E &= \frac{4{,}000{,}000 \times 1{,}000}{0.1 \times 10^8} \\ &= 400 \text{ volts.} \end{aligned}$$

Let the black dots 1, 2, 3, 4, Fig. 30, represent the successive positions of one side of a closed conductor as it moves across a magnetic line. When the conductor approaches a magnetic line, the line, being elastic, is not cut at once, but is bent as shown at A. As the motion of the conductor continues, this depression of the line increases as at B, and the line wraps itself around the conductor as at C. When the limit of elasticity, so to speak, of the line

has been reached and it is ruptured the two ends at once combine, making as before one continuous line, and at the same time the extended or bent portion of the line closes, forming a circle of the magnetic line around the wire. Therefore, by the mechanical process of carrying a portion of a closed conductor across a magnetic field, a circular magnetic field is developed around the con-

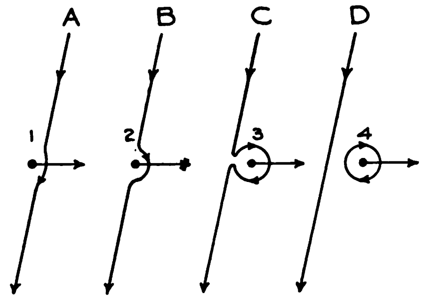


Fig. 30.

ductor, and accordingly a current of electricity is developed and flows in the conductor.

It is also quite evident that the direction in which the lines wrap themselves is determined by the direction of motion with reference to the magnetic field. In Fig. 30 the conductor was assumed to move from left to right. If the conductor moves from

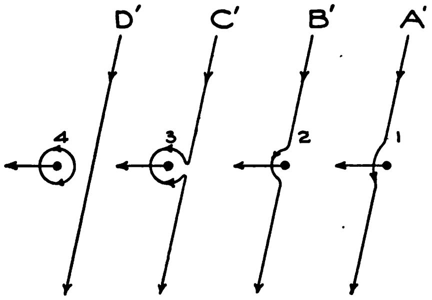


Fig. 31.

right to left, the conditions will be as shown in Fig. 31. An examination of the diagram clearly shows that the direction of the circular field at (4) is counter-clockwise, while in Fig. 30 the direction of the circular field is clockwise.

30. Relative Direction of Magnetic Field and Induced Electromotive Force.—An experiment[1] can easily be performed which will

[1] Exp. 18, "Elementary Magnetism and Electricity."

show that the polarity of the ends A and B of the wire, Fig. 28, will depend upon the direction in which it moves across the magnetic field. If it moves down, A may be positive and B negative, and if it moves in the opposite direction the polarity is reversed. The direction of the induced electromotive force depends on the direction of the magnetic lines and also upon the direction of motion of the conductor which cuts the lines.

Let Fig. 32 represent a section of a magnetic field by the plane of the paper and assume that the positive direction is from below upward.

If a pair of metal rails r_1 and r_2 be placed as shown and connected by conductors to a galvanometer G, which is used to detect the flow of currents, and a metal rod be moved across the field

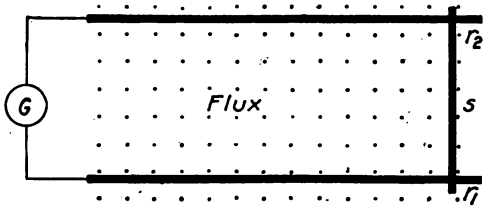


FIG. 32.

while in contact with the rails, a current will flow through the galvanometer circuit. This flow of current is due to the cutting of the magnetic lines by the conductor. If the rod be moved toward the left, the end resting on r_2 will be positive and the end near r_1 will be negative. That is, the current will flow from r_1 through the conductor s to r_2, through r_2 and the galvanometer to r_1, making a complete circuit. If the rod be moved in the opposite direction, that is from right to left, the direction of current flow will be reversed. Also, if the positive direction of the magnetic flux be from above downward, and the rod be slid from left to right the conductor will be positive at r_2 and negative at r_1. Sliding the conductor in the opposite direction will again reverse its polarity.

Reversing either the direction of motion of the conductor, or the direction of the magnetic field, reverses the direction of the induced electromotive force.

In Article 29 it was shown that whenever a conductor moves in any direction through a magnetic field the induced electromotive force is given by

$$e = BlV \cos \beta \sin \theta \cos \alpha,$$

where β is the angle the direction of motion makes with a normal to the conductor, θ is the angle the direction of motion makes with the magnetic lines, and α is the angle the conductor makes with a plane normal to the magnetic field.

In practice β and α are each zero, that is the conductor is moved at right angles to its length, and is in a plane normal to the magnetic lines. The expression for e then becomes

$$e = BlV \sin \theta.$$

When the conductor moves at right angles to the magnetic lines, that is when $\theta = 90°$, there are three quantities mutually perpendicular to each other; namely, the magnetic lines, the motion of the conductor, and the induced electromotive force.

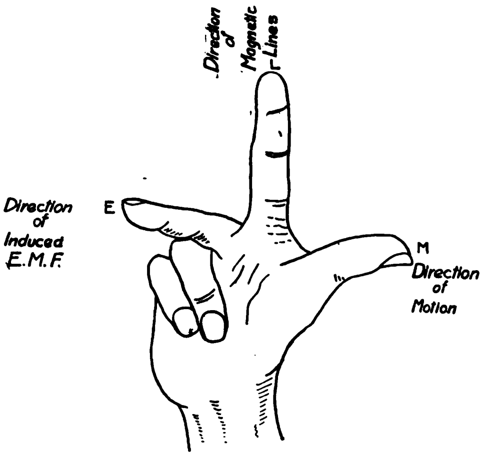


FIG. 33.

Many rules have been formulated to aid in remembering the relations between these three quantities. Perhaps the right-hand rule of Fleming is as simple and easily remembered as any.

RULE.—*If the middle finger, forefinger and thumb of the right hand be extended so that each is perpendicular to the plane containing the other two, Fig. 33, the direction of the digits will represent the directions of the three quantities as follows:*

Direction of thumb from hand out will represent the direction of motion; the direction of the forefinger will represent the direction of the magnetic field; and the direction of the middle finger the direction of the induced electromotive force. This relation can easily

be remembered by the aid of the three letters E, L, M. Thus E at the tip of the middle finger, L at the tip of the forefinger, and M at the tip of the thumb, Fig. 33, spell *elm*, and at the same time give the space relation between the electromotive force, E; lines of magnetism, L; and motion, M.

Another simple method of remembering this relation is to consider the magnetic lines to be elastic and that as the con-

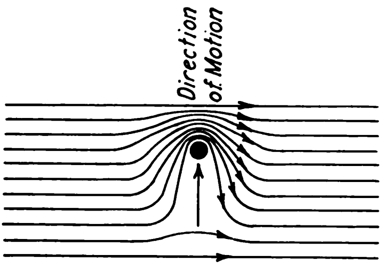


Fig. 34.

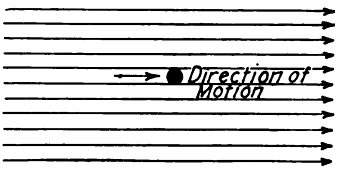


Fig. 35.

ductor moves across the field, the lines tend to wrap themselves around the conductor as indicated in Fig. 34. If the positive direction of the magnetic lines is clockwise as shown, the induced electromotive force is away from the observer, or into the paper. If the positive direction of the lines is counter-clockwise the induced electromotive force is directed toward the observer, or

Fig. 36.

out from the paper. It is quite important that some general rule be remembered.

Recapitulation

1. *Electromagnetic induction* is the principle of inducing an electromotive force by the relative motion of a conductor and a magnetic field.

2. When a conductor moves across a magnetic field, the electromotive force induced in a conductor depends on the following conditions: *First*, the number of magnetic lines per unit area of the magnetic field, that is, the *flux density; second*, the length of conductor which is cutting the magnetic field

third, the velocity of the conductor with respect to the field, that is, the rate of change of position between the conductor and the field; *fourth*, the direction of motion between the conductor and the field. If the conductor is moved parallel to the field flux as in Fig. 35, there is no cutting of lines of induction and, hence, no pressure is induced. If the motion of the conductor is at right angles to the flux as in Fig. 34, the rate of cutting with a given velocity of conductor, will be a maximum. Motion of the conductor in the field in any direction which makes an angle between 0° and 90° to the flux as in Fig. 36 will produce a pressure which is dependent on the sine of the angle between the direction of the motion and the direction of flux.

3. The value of the induced electromotive force any instant is given by

$$e = BlV \sin \theta,$$

where B = flux density per square centimeter,
l = length of conductor in centimeters,
V = speed of conductor in centimeters per second,
and θ = angle the direction of motion makes with the direction of magnetic lines.

4. The average value of the electromotive force induced in one conductor is

$$E = \frac{\Phi}{t} \text{ absolute units,}$$

where Φ is the flux cut in t seconds.

As 1 volt is equal to 100,000,000 = 10^8 absolute units,

$$E = \frac{\Phi}{t \times 10^8} \text{ volts.}$$

If n conductors cut a flux Φ in t seconds, then the average pressure in each is

$$E = \frac{\Phi}{t}.$$

And if these conductors are connected so that the pressure in one is added to that in the other, then

$$E = \frac{n\Phi}{t}$$

$$= \frac{n\Phi}{t \times 10^8} \text{ volts.}$$

5. The relative direction of the induced electromotive force with reference to the direction of the magnetic flux and the direction of motion may be determined by the following:

Rule.—*Bend the middle finger, the forefinger, and thumb so that any one shall be at right angles to the plane of the other two; then if the forefinger points to the positive direction of the magnetic lines, and the thumb in the direction of the motion of the conductor, the electromotive force induced will be in the direction of the middle finger.*

CHAPTER IV

UNITS OF MEASUREMENT

31. Introduction.—Some of the more common electrical and magnetic units have already been defined. In this chapter we shall collect these definitions and add definitions of other terms which are met in electrical and magnetic measurements. In addition a more complete and systematic discussion of different systems of units and their importance will be taken up.

32. Measurement.—In order that physical quantities may be compared and that their effects and relations may be calculated, they must be measured and their magnitudes or relative sizes determined. For the purpose of measurement, units are necessary. The unit is always some arbitrarily chosen magnitude of like quantity. For instance, the fundamental unit of length in most electrical calculations is a fractional part of the meter. The meter is defined as the distance, at the temperature of melting ice, between two points on a certain platinum iridium bar deposited at the International Bureau of Weights and Measures at Sevres, France. One one-hundredth of this length is the centimeter which is the unit of length used in most scientific calculations. In the British system of units the fundamental arbitrary unit of length is the yard, one-third of which, the foot, is commonly used in engineering calculations.

What is true with respect to the arbitrary nature of the unit of length is true with respect to the units of other quantities.

The measurement of a physical quantity consists in comparing its magnitude, or effect, with the magnitude, or effect, of the arbitrarily chosen unit as the standard of comparison. The magnitude of the quantity measured is then expressed in terms of that unit, and the expression consists of two parts; a numerical part, and the part which names the unit with which it has been compared. Thus we may give the length of a wire as 1,000 *feet* or as 1,000 *meters*. Merely the number 1,000 will give no idea of the length, but the number must be followed by the name of the unit of measure. The numerical part will vary inversely with

the size of the unit employed. Thus a distance may be expressed as 1 *mile*, 1,760 *yards*, or 5,280 *feet*. The distance is the same in each instance, but as the size of the unit of measure decreases the numerical part of the expression increases.

Systems of Units.—Fundamental concepts of physical quantities are those of length, mass, and time, and most physical quantities may be expressed in terms of these. For this reason the units of *length*, *mass*, and *time* are called *fundamental units*, and all other units which can be expressed in terms of these are called derived units. A system of units which consists of the fundamental units and derived units based on these is called an *absolute* system. In the absolute system commonly used the fundamental units

FIG. 37.

are the *centimeter*, the *gram* and the *second*, and the system is for this reason called the c.g.s. system. The corresponding units in the English system are the *foot*, the *pound*, and the *second*.

The *gram* is the $\frac{1}{1,000}$ part of a mass of metal called the kilogram, Fig. 37. It was intended that the gram should represent the mass of 1 cubic centimeter of distilled water at the temperature of 4°C. Although this is not quite correct, nevertheless, for all practical purposes we may regard the mass of 1 cubic centimeter of distilled water at 4°C. as equal to 1 gram.

The *second* is defined as the $\frac{1}{86,400}$ part of a mean solar day. By mean solar day is meant, the average time for a year between the successive passages of the sun across the meridian. The *meter* has already been defined.

33. Derived Units.—Units of quantities depending on powers greater than unity of the fundamental units of length, mass, and time, are called derived units. Thus the units for the measurement of surface, volume, velocity, force, work, current, electromotive force, etc., can all be expressed in terms of the fundamental units, and are, therefore, derived units. The number of derived units is limited solely by the number of physical quantities to be measured. In electrical measurements and calculations, with which we are at present concerned, two kinds of derived units are commonly used. These are *absolute* units and *practical* units. The absolute units are those based directly upon the three fundamental units. They can be expressed directly in terms of the fundamental units without any multiplying or conversion factors.

The absolute units are, however, too small in some cases, and too large in others for convenient use, and hence, for practical calculations and measurements, certain multiples of the absolute units have been chosen and named. These are called practical units. These will be defined later.

34. Magnetic and Electrical Units.—The absolute units employed in electrical and magnetic measurements are based on two different fundamental assumptions. In one system the repulsive force between two electrical charges is made the basis. This system is known as the *electrostatic system of units*. In the other the repulsion between two magnetic poles, or quantities of magnetism, is taken as the basis. This is known as the *electromagnetic* system of units. Most electrical measurements are made with the electromagnetic units. There are certain relations between these two systems of units the values of which have been determined by experiment.

The fundamental bases of both the electrostatic and electromagnetic systems of units are force and work. The absolute unit of force the *dyne* is defined as that force which when applied to a gram mass will give it an acceleration of 1 centimeter per second per second. This is known as the absolute or c.g.s. unit of force. A pound force is approximately equal to 444,800 dynes.

The absolute unit of work is the *erg* which is defined as the work spent or done by a force of 1 dyne acting through a distance of 1 centimeter. For a fuller discussion of work see next chapter.

35. Electrostatic Units.—The more common electrostatic

units are those of quantity of electricity, difference of electrical potential, and of capacity.

(a) *The Unit of Quantity.*—The unit of quantity of electricity is that quantity which will exert a force of 1 dyne upon an equal and like quantity at a distance of 1 centimeter in air.

(b) *The Unit Difference of Potential.*—A unit difference of electrical potential exists between two points when it requires an expenditure of 1 erg of work to bring a plus unit of electrical quantity from one point to the other point.

(c) *A unit capacity* is that electrical capacity of a conductor which requires a charge of one electrostatic unit of quantity to produce a unit difference of potential. These electrostatic units have no names, and will be little used by the student. They are given here mainly for reference and comparison.

36. Electromagnetic System of Units.—As already pointed out the electromagnetic units are based on the force exerted between two like magnetic poles. These units may be considered under two heads, *magnetic* and *electrical.* The magnetic units are those used in the measurement of magnetic quantities and the electrical units are those used in measuring electrical quantities.

37. Magnetic Units.—The more common magnetic units are the following:

(a) *Unit Magnet Pole.*—This has already been defined. See Article 6.

(b) *Unit Difference of Magnetomotive Force.*—A unit difference of magnetomotive force exists between two points when it requires an expenditure of 1 erg of work to move a north-seeking, unit pole from one point to the other against the magnetic forces. This unit is called the *gilbert.*

(c) *Unit Intensity of Magnetic Field.*—This has been defined. See Article 8. It is called the *gauss.*

(d) *Unit of magnetic reluctance* is that reluctance which requires a unit of magnetomotive force to develop one line of magnetic flux. It is called an *oersted.*

(e) *Unit of Flux Density.*—The unit of flux density is one line of induction per square centimeter, or 1 maxwell per square centimeter.

38. Electrical Units.—The electrical quantities for the measurement of which units are necessary are current, quantity of electricity or charge, electromotive force, resistance, power, work, capacity, also called capacitance or permittance, and inductance.

The units of power and work are discussed in the next chapter.

(*a*) *The Unit of Current.*—Whenever a current of electricity flows through or along a wire, a magnetic field is built up around the wire. This magnetic field is capable of exerting a force upon a magnetic pole. The unit current is defined in terms of the work spent in moving a unit magnetic pole around a current-carrying wire as follows:

An absolute unit of current is that current which requires an expenditure of 4π ergs to carry a unit magnetic pole once around the current.

Another definition which has already been given is the following: The absolute electromagnetic unit of current is that current which when flowing through a conductor bent into a circle of 1 centimeter radius, exerts a force of 2π dynes on a unit pole at the center of the circle of which the conductor is the circumference. The two definitions are equivalent.

This unit of current is too large for practical purposes. It has no name but is sometimes called the *abampere*. The prefix *ab* is the first syllable of the word *absolute*.

(*b*) *The absolute unit of quantity* is that quantity of electricity transferred by 1 abampere in 1 second. It is sometimes designated the *abcoulomb*. This unit is also too large for practical purposes.

(*c*) *Difference of Electrical Potential or Electromotive Force.*—A difference of electrical potential is said to exist between two points if, when the two points are joined by a conducting material, an electric current will flow between the points. Every electric generator is primarily a device for developing and maintaining a difference of potential or electromotive force. Electromotive force may then be considered as the real cause of an electric current. It may be produced or maintained in several different ways, only one of which is of interest at present and this has been explained in the previous chapter. The essential principle is that whenever a wire is moved across a magnetic field an electromotive force is induced in the wire. One *absolute unit* of electromotive force is induced in the wire when it cuts 1 maxwell per second. This unit is the *abvolt*. It is entirely too small for practical calculations and measurements.

(*d*) *The absolute unit of resistance* is that resistance which requires an electromotive force of 1 abvolt to force 1 abampere

through the resistance. This is also a very small unit and for practical purposes another one is used.

(*e*) The *absolute unit of capacity,* or better *capacitance,* is the capacitance of a conductor which will be charged to a difference of potential of 1 abvolt by 1 abcoulomb.

The *absolute unit of work* is *the erg,* which has been defined in Article 34, and the absolute unit of power is the rate of doing 1 erg per second.

(*f*) *Inductance.*—It has been shown that when a magnetic field cuts across a conductor an electromotive force is induced in

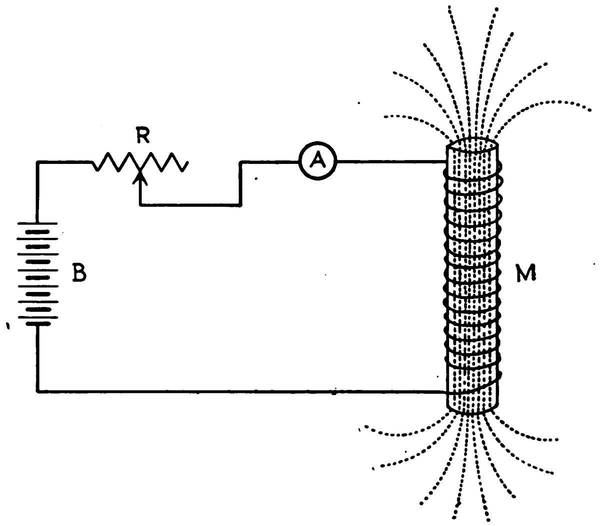


FIG. 38.

the conductor. The source of the magnetic field is immaterial. Whenever a circuit is closed so that a current can flow, the flow of current establishes a magnetic field around the conductor. This building up of the magnetic field has the same effect as if the conductor were moved across a magnetic field, that is, an electromotive force is developed in the conductor.

Consider the case represented by Fig. 38 where a battery B supplies current through a variable resistance R to an electromagnet M. Let us suppose the circuit open and no initial or residual magnetism in the core. Upon closing the circuit a current will begin to flow through the electromagnet coil. This current will magnetize the core and thus cause a number of mag-

netic lines to thread through the coil. If the resistance R is varied, the current will change and, consequently, the number of magnetic lines threading through the coil is either increased or decreased. In other words, any change in the current is accompanied by a change in the magnetic flux passing through the coil.

According to the principle of electromagnetic induction, whenever the magnetic flux in the coil changes, an electromotive force is induced in it. The electromotive force induced by the building up or decay of the magnetic field within the coil, due to the variation of current in the coil, is called the electromotive force of *self-induction.* The induced electromotive force is in such a direction as to oppose the applied electromotive force. In other words, while the current is changing the electromotive force of self-induction opposes any change.

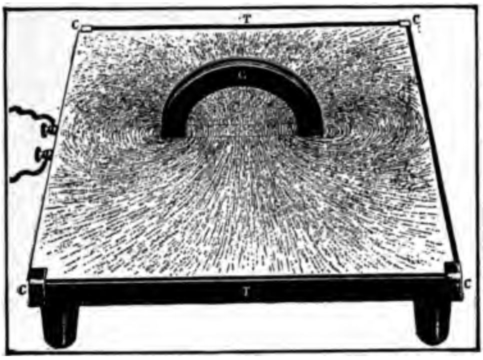


FIG. 39.

From Fig. 39 it is evident that each magnetic line through the center of the coil is linked with each turn; or what amounts to the same thing, the lines due to each turn are linked with every other turn as well. The electromotive force of self-induction then depends not only upon the current but also upon the arrangement of conductors in the coil. If ϕ is the total flux due to one turn through the coil, and if N is the number of turns, the total flux is $N\phi$. This total flux is proportional to the current and hence we may write

$$\Phi = N\phi = LI.$$

The constant L is called the coefficient of self-induction, or simply the *self-inductance* of the coil. Dividing by I we have

$$L = \frac{\Phi}{I}.$$

From this expression the self-inductance or coefficient of self-induction of a coil may be defined as the ratio of the flux threading through the coil to the current producing it.

The electromotive force of self-induction depends upon the time rate of change of the magnetic field in exactly the same manner as when the conductor is moved across a magnetic flux. Then if

$$\Phi = LI,$$

$$\frac{\Phi}{t} = \frac{LI}{t}$$

if Φ changes uniformly during the time t. As $\frac{\Phi}{t}$ is the time rate of change of flux, it is equal to the electromotive force of self-induction; hence

$$E = \frac{\Phi}{t} = \frac{LI}{t},$$

where $\frac{I}{t}$ is the time rate of change of current. Dividing by $\frac{I}{t}$ we get $L = \frac{E}{\frac{I}{t}}$. If Φ does not change at a uniform rate, we may represent the time rate of change by $\frac{\vartheta\Phi}{\vartheta t} = L\frac{\vartheta i}{\vartheta t}$, whence in general $E = L\frac{\vartheta i}{\vartheta t}$, and $L = \frac{E}{\frac{\vartheta i}{\vartheta t}}$. According to this expression the inductance L of a coil may be defined as the ratio of the induced electromotive force to the time rate of change of current.

(*g*) *Mutual Induction.*—When two coils are situated so that the magnetic flux developed by a current in one coil threads through the other coil, a similar physical reaction or phenomenon results. Thus in Fig. 40 a current in coil A will produce a flux in the iron core and this flux will pass through coil B. This flux will induce an electromotive force in coil B. The development of an electromotive force in one coil by a current flowing in an adjacent coil is called mutual induction.

Self and mutual inductions are physical phenomena of the same nature, and hence the same unit is used for their measurement.

The *unit of inductance* is defined as the inductance in a circuit in which the induced electromotive force is 1 abvolt when the current changes at the rate of 1 abampere per second, or it

may be defined as that inductance of a circuit in which unit flux is produced by unit current.

39. Practical Electrical Units.—The absolute units defined in the preceding articles are not of a convenient magnitude to be used in practical measurement, and furthermore they are not readily determined. For these reasons multiples of these units have been chosen for engineering calculations and measurements. The practical units have also been defined in terms of certain definite concrete standards which can be reproduced with reasonable accuracy.

40. Electric Current.—The transference of energy by water through pipes is in many ways analogous to the transference of energy by electricity, the terminology of the former method is, therefore, to some extent used in the latter.

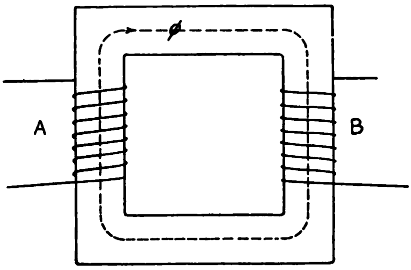


Fig. 40.

When water flows through pipes, the energy transferred by it in a given time depends upon the current and head, or pressure. The current is the number of gallons or cubic feet of water flowing per second or some other unit of time. The current is then the rate of flow of water.

Electrical energy may be transferred along a conductor, and while the energy is being transferred the conductor is surrounded by a magnetic field. The transfer of energy is said to be by means of a current of electricity. Thus, the rate of flow of electricity is also called a current. The two cases are evidently analogous.

In measuring a water current it is possible to measure the quantity of water discharged during a given time, and thus the rate of flow. It is not practical to measure an electric current in this way. The electric current is measured by means of its effect, and any effect which is proportional to some power of the current strength

may be used for determining unit current, and hence, for measuring the current. The practical unit current has been defined in accordance with Faraday's first law as follows:

The *ampere* is the unvarying electric current which, when passed through a standard solution of nitrate of silver in water, deposits silver at the rate of 0.00111800 grams per second. An ampere will thus deposit 4.025 grams of silver per hour.

The ampere is one-tenth of the absolute electromagnetic unit of current.

Practical Unit of Quantity.—The quantity of water flowing through any given pipe in a given time may be expressed as the strength of current multiplied by the time. That is, if a unit current gives a cubic foot of water per second, a two-unit current would give 2 cubic feet per second, or 4 cubic feet in 2 seconds.

Similarly, a unit current of electricity flowing for 1 second gives a definite quantity of electricity. This quantity is called the *coulomb* and is defined as the quantity of electricity conveyed by a current of 1 ampere in 1 second of time. The total quantity conveyed by a current of I amperes in t seconds is then given by

$$Q = It, \text{ assuming } I \text{ to be constant.}$$

A coulomb is also equal to $\frac{1}{10}$ or 10^{-1} times the absolute electromagnetic unit of quantity.

42. Resistance.—Every electrical conductor offers a resistance to the flow of electricity. This resistance depends upon the material of which the conductor is made, the length of the conductor, and its cross-sectional area. The resistance of a conductor is analogous to the resistance a water pipe offers to the flow of water. This resistance will depend upon the roughness of its surface, or upon the material of which it is made. A long pipe will offer more resistance than a short pipe of the same diameter, and a pipe of large diameter will offer less resistance than one of the same length but of smaller diameter. It must be remembered, however, that the cause of the resistance of a conductor to the flow of electrical current is not the same as the cause of the resistance of a water pipe to the flow of water. They are analogous only.

The resistance of any conductor can then be written in the following form:

$$R = \frac{rl}{A},$$

where R is the total resistance, r the resistance of a piece of the conductor of unit length and of unit cross-section, A its cross-sectional area, and l its length.

The *ohm* is the unit of resistance and is defined as the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams mass, of a constant cross-sectional area and of a length of 106.3 centimeters. The ohm is equal to $10^9 = 1{,}000{,}000{,}000$ times the absolute electromagnetic unit of resistance.

The ohm is thus a definite quantity and the resistance of any conductor is expressed in terms of it. In the formula $R = \frac{rl}{A}$, l and A may be expressed in any units, provided r expresses a resistance based on these units. The definition given for the ohm assumes l to be in centimeters and A in square centimeters. In this country the American wire gage (Brown and Sharpe) has been generally adopted where a gage is to be used. In many cases it is better to specify the actual diameter or cross-sectional area of a wire, and for this purpose the "mil system" has been introduced. In this system the *mil* is the unit of length and is equal to 0.001 inch.

Since the areas of any two circles are proportional to the squares of their diameters, if the area of a circle 1 mil in diameter be taken as the unit area, the area of any other circle may be expressed as the square of its diameter in mils. The unit area is called the circular mil and is, as above expressed, the area of a circle 0.001 inch in diameter. Area in circular mils is equal to diameter in mils squared, and the area expressed in square measure is equal to $0.7854 \times d^2$ (diameter squared). The circular mil is, therefore, equal to 0.7854 of a square mil.

It is seldom necessary to convert the area of round conductors into square measure. The wire tables which are in common use usually give the sizes in the American wire gage (A.w.g.), its diameter in mils, its area in circular mils, and various other properties of wire depending on the completeness of the tables.[1]

Wires larger than No. 0000 A.w.g., that is, of a greater diameter than 0.46 inch, are usually designated by their diameters in mils or their cross-sectional area in circular mils.

The unit of a conductor most commonly used is a conductor 1 foot long and 1 mil in diameter called the mil-foot. The resist-

[1] *Circular* No. 31, Bureau of Standards.

ance of a mil-foot of copper of 98 per cent. conductivity is 9.61 ohms at 0°C. or 32°F. This value may be used in our resistance formula which then becomes

$$R = \frac{9.61l}{A},$$

l being expressed in feet and A in circular mils.

43. Change of Resistance with Temperature.—The resistance of most conductors changes with the temperature. The resistance of pure metallic conductors increases with increase in temperature. For pure metals the increase per ohm per degree is practically the same for all. This increase per ohm per degree change in temperature is called *temperature coefficient of resistance,* and for copper it is nearly 0.00393 per ohm per degree at 20°C. The resistance of a conductor at any temperature t°C. is given by the following:

$$R_t = R_{20}\,[1 + a(t - 20)].$$

R_{20} is the resistance of conductor in ohms at 20°C., a the temperature coefficient, and t the temperature, in degrees Centigrade.

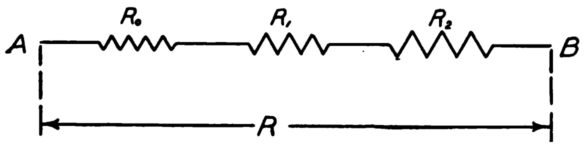


FIG. 41.

The resistance of most alloys also increases with increase in temperature, but to a much smaller extent than pure metals. Thus an alloy of 84 parts by weight of copper, 12 parts by weight of nickel, and 4 parts by weight of manganese, called manganin, has a temperature coefficient of resistance which is negligible for practical purposes. Although the temperature coefficient of manganin is very slight, it is positive between 0° and about 50°C. When the temperature is increased above 50°C. the resistance of manganin slightly decreases.

Carbon and all acid and salt solutions have negative temperature coefficients of resistance. That is, the resistance of these decreases as the temperature increases.

44. Conductors in Series.—When several conductors are connected in series, that is, end to end, the combined resistance is the sum of the resistances of the several conductors. Thus the

resistance R, Fig. 41, between the points A and B is equal to $R_0 + R_1 + R_2$.

45. Conductors in Parallel.—The conductance of a conductor is defined as the reciprocal of the resistance of the conductor. If R is the resistance then $\frac{1}{R}$ is the conductance. When conductors are connected in parallel the resultant or joint conductance is equal to the sum of the conductances of the several conductors. The manner of computing the joint resistance will then be readily understood from Fig. 42. If R_1, R_2, and R_3 are the several resistances connecting the points A and B, the conductances of these branches are $\frac{1}{R_1}$, $\frac{1}{R_2}$ and $\frac{1}{R_3}$ respectively. Calling the

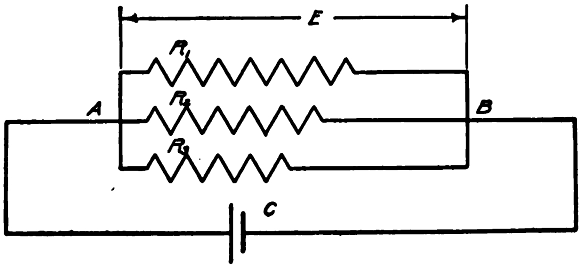


FIG. 42.

joint resistance R, the joint conductance is $\frac{1}{R}$, and according to what has just been said above we have

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{R_2R_3 + R_1R_2 + R_1R_3}{R_1R_2R_3},$$

and

$$R = \frac{R_1R_2R_3}{R_1R_2 + R_1R_3 + R_2R_3}.$$

In general, the joint resistance of several conductors connected in parallel is equal to the product of the several resistances divided by the sum of the partial products formed by multiplying together all of the resistances less one. The same resistance must not appear in any product more than once.

Example

Five resistances of 10, 15, 20, 25, and 30 ohms are connected in parallel. Calculate the joint resistance.

Solution.—Given

$$R_1 = 10 \text{ ohms},$$
$$R_2 = 15 \text{ ohms},$$
$$R_3 = 20 \text{ ohms},$$
$$R_4 = 25 \text{ ohms},$$
$$R_5 = 30 \text{ ohms},$$

$$R = \frac{R_1R_2R_3R_4R_5}{R_1R_2R_3R_4 + R_1R_2R_3R_5 + R_1R_2R_4R_5 + R_1R_3R_4R_5 + R_2R_3R_4R_5}.$$

$$R_1R_2R_3R_4R_5 = 10 \times 15 \times 20 \times 25 \times 30 = 2{,}250{,}000$$

$$R_1R_2R_3R_4 = 10 \times 15 \times 20 \times 25 = 75{,}000$$

$$R_1R_2R_3R_5 = 10 \times 15 \times 20 \times 30 = 90{,}000$$

$$R_1R_2R_4R_5 = 10 \times 15 \times 25 \times 30 = 112{,}500$$

$$R_1R_3R_4R_5 = 10 \times 20 \times 25 \times 30 = 150{,}000$$

$$R_2R_3R_4R_5 = 15 \times 20 \times 25 \times 30 = 225{,}000$$

Sum of partial products $= 652{,}500$

$$R = \frac{2{,}250{,}000}{652{,}500} = 3.46 \text{ ohms}.$$

46. Divided Circuits—Kirchoff's Laws.—In addition to the simple series and parallel connections shown in Figs. 41 and 42, conductors may be connected in various and much more complicated ways. The several electrical quantities involved in such a network can be evaluated by the aid of what are known as Kirchoff's laws; these are two in number as follows:

(*a*) If several conductors carrying currents of different intensities meet at a point, the sum of the intensities of all the currents which flow toward the junction point through these conductors is equal to the sum of all those which recede from it; or, in other words, the algebraic sum of all the currents which approach the point through the wires which meet there is zero.

(*b*) If out of any network of wires which form a complex conductor a number of wires which form a closed circuit be chosen, and if starting at any point, we follow around the closed circuit in either direction, calling all currents positive which flow in the direction that we trace the circuit, and all those which flow in the opposite direction negative; and also calling all sources

of electromotive force positive that we encounter in the circuit positive when they tend to send the current in the direction of motion, and when they tend to send the current in the opposite direction negative, then the algebraic sum of all the products formed by multiplying the resistance of each conductor by the current flowing through it and all the electromotive forces encountered is zero. In brief, the algebraic sum of the electromotive forces and IR drops in a closed circuit is zero.

These two laws are merely the statements of experimental facts. The first is an immediate consequence of the fact that there can be no growing accumulation of electricity anywhere in a circuit through which a steady current is flowing.

That the second law is also true will be quite evident if we compare the voltage drops and rises in potential around a circuit

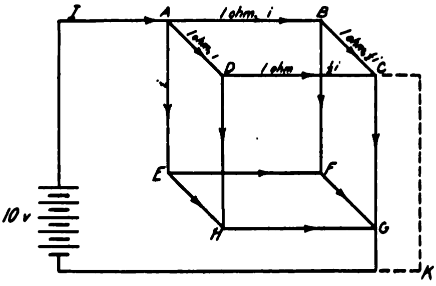


FIG. 43.

with the descents and ascents in a road which traverses a country making a complete circuit. It is very evident that a traveller following such a road will descend just as far as he ascends when he returns to the starting point. Thus if we call a descent a negative elevation and an ascent a positive elevation, the algebraic sum of the elevations is zero. Examples will serve to make the applications of these two laws more clear.

Example

1. Fig. 43 represents a cube each edge of which is a conductor of 1 ohm resistance. A pressure of 10 volts is connected to two diagonally opposite corners. Find the total current in the circuit and also the resistance between the two corners A and G.

Solution.—

Let I = current supplied by the battery,

Let i = current in conductor AB.

hen due to the symmetrical arrangement of the conductors

$$i = \text{current in } AD,\ AE,\ FG,\ HG, \text{ and } CG,$$

and

$$\frac{1}{2}i = \text{current in } BC,\ DC,\ BF,\ DH,\ EF, \text{ and } EH.$$

By Kirchoff's first law we have for the junction point A,

$$I = i + i + i.$$

Or

$$I = 3i,$$

and

$$i = \frac{1}{3}I$$

$$\frac{1}{2}i = \frac{1}{6}I.$$

By the second law, for the closed circuit $ABCG$ and by way of the battery back to A we have, assuming the battery wires to have no resistance:

$$i \times 1 + \frac{1}{2}i \times 1 + i \times 1 - 10 = 0,$$

or

$$\frac{1}{3}I + \frac{1}{6}I + \frac{1}{3}I = 10,$$

$$\frac{5}{6}I = 10,$$

$$I = 12 \text{ amperes.}$$

But by Ohm's law,

$$R = \frac{E}{I}, \text{ hence } R = \frac{10}{12} = \frac{5}{6} \text{ ohm.}$$

2. Calculate the resistance between the points A and C, and the current when the battery is connected to the points A and C.

Solution.—From the symmetry of the figure, the currents in AB, AD, BC, and DC are equal. Call one of these currents i_1, and let i_2 = the current in AE. This is also the current in GC, EF, FG. EH and HG each carry a current equal to $\frac{1}{2}i_2$.

By Kirchoff's law we have

$$I = i_1 + i_1 + i_2 = 2i_1 + i_2.$$

By the second law for the circuit $ADHE$ we have

$$i_1 \times 1 + 0 \times 1 - \frac{1}{2}i_2 1 - i_2 \times 1 = 0,$$

or

$$i_2 = \frac{2}{3}i_1.$$

Applying the second law to the circuit $ABCK$ and back to A gives

$$I \times 0 + i_1 \times 1 + i_1 \times 1 - 10 = 0,$$

whence

$$i_1 = 5,$$

$$i_2 = \frac{10}{3},$$

$$I = 2i_1 + i_2 = 10 + \frac{10}{3} = 13\tfrac{1}{3} \text{ amperes.}$$

$$R = \frac{E}{I} = \frac{10}{\frac{40}{3}} = \frac{3}{4} \text{ ohm.}$$

Further applications of these laws will be given in connection with three-wire circuits.

47. The Practical Unit of Electromotive Force.—Since the resistance of a conductor is comparable to the resistance offered by a pipe to the flow of water, and the electrical current is comparable to the current of water, we may compare the electromotive force or electrical pressure to the water pressure causing a flow of water. Although this comparison is not exact, it still serves to give a better understanding of the relation of the electrical quantities involved. Water pressure can be measured in terms of pounds per square inch, but usually it is expressed as a head of so many feet. In the same way, the difference of electrical pressure between the terminals of a battery may be considered as a difference of electrical level. The current will then flow from a point of higher to a point of lower electrical level, when the circuit is closed. This difference of electrical pressure or electromotive force, is expressed in volts, and the *volt* is defined as that difference of pressure which will cause a current of 1 ampere to flow through a resistance of 1 ohm. More concretely the *volt* may be defined as $\frac{100,000}{101,830}$ of the electromotive force of the Weston normal cell at a temperature of 20°C. One volt is equal to 10^8 absolute units of electromotive force.

48. Practical Unit of Inductance.—The practical unit of inductance is the *henry*. It is defined as the inductance in a circuit in which the induced electromotive force is 1 volt, when the current changes at the rate of 1 ampere per second. The henry is equal o 10^9 absolute electromagnetic units.

49. Practical Unit of Capacitance.—If two metal plates be eparated by a good insulator and the two plates be connected to source of electrical pressure, a momentary current will flow into e plates. The intensity of the current will depend upon the bility of the plates to hold a charge of electricity. This ability

of a conductor or a system of conductors, to store electricity is called electrical capacitance. The capacitance of a system of conductors is determined by their arrangement, number, and material separating them. The quantity of electricity that a condenser will hold is determined by the capacitance of the condenser and by the electrical pressure applied. Algebraically this is expressed by

$$Q = EC,$$

where Q is the quantity of electricity, E the pressure, and C the capacitance.

Farad.—The unit of capacitance is called the *farad* and is the *capacitance* of a condenser *which is charged* to a difference of pressure of 1 volt by 1 coulomb.

The farad is equal to $10^{-9} = \frac{1}{1,000,000,000}$ of the absolute electromagnetic unit of capacitance. But even the farad is far too large for ordinary use, and it is customary to express capacitance in terms of *microfarads,* a microfarad being (10^{-6}) one-millionth of a farad. A microfarad is thus 10^{-15} of the size of the absolute electromagnetic unit of capacitance.

50. Ohm's Law.—The fundamental relation between current and electromotive force was enunciated by Dr. G. S. Ohm in 1827, and is known as Ohm's law. It may be stated as follows:

The current strength in any circuit is directly proportional to the sum of all the electromotive forces in the circuit. This relation expressed algebraically is

$$E = KI,$$

or

$$\frac{E}{I} = K, \text{ a constant.}$$

This holds for both direct- and alternating-current circuits so long as the physical conditions surrounding the circuit remain unchanged. For direct-current circuits K is equal to what is called the resistance of the circuit and under these conditions

$$E = RI,$$

or

$$\frac{E}{I} = R.$$

Thus the ratio of the electromotive force to current is constant

so long as physical conditions remain constant. If, for instance, the temperature changes, this ratio will change. This is explained by saying that the resistance changes.

On alternating-current circuits the total electromotive force must include the electromotive forces of mutual induction, self-induction, and capacitance. When these are considered, Ohm's law as stated still holds.

51. Conversion Factors.—Although it is not often necessary to convert the electrostatic units into the electromagnetic or practical units, it is sometimes essential. Likewise many calculations are still made in the English system of units. To facilitate these calculations the following conversion factors are appended:

ELECTRICAL UNITS

Practical units	Absolute electromagnetic units	Absolute electrostatic units
1 ampere	10^{-1} abampere	3×10^{9} units
1 coulomb	10^{-1} abcoulombs	3×10^{9} units
1 volt	10^{8} abvolts	$\frac{1}{3} \times 10^{-2}$ units
1 ohm	10^{9} abohms	$\frac{1}{9} \times 10^{-11}$ units
1 henry	10^{9} abhenrys	$\frac{1}{9} \times 10^{-11}$ units
1 farad	10^{-9} abfarads	9×10^{11} units
1 joule	10^{7} ergs	
1 watt	1 joule per second	10^{7} ergs per second

Recapitulation

1. The fundamental scientific units of measurement are the centimeter, gram, and second.

2. Absolute units of measurement are those based strictly upon the fundamental units and can be expressed directly in terms of the fundamental units without any multiplying or conversion factors.

3. The basis of the electrostatic system of units is the force of repulsion between two equal and like electric charges.

4. The basis of the electromagnetic system of units is the force of repulsion between two equal and like magnetic poles. The electromagnetic system of units is the one commonly used in electrical engineering.

5. The magnetic units of the electromagnetic system are:

Unit Magnet Pole.—A magnetic pole is said to have unit strength if it exerts a force of 1 dyne upon an equal and like pole at a distance of 1 centimeter in air. All magnetic material is assumed to be at infinite distance.

Unit Difference of Magnetomotive Force.—A unit difference of magnetomotive force is said to exist between two points when it requires an expenditure of 1 erg of work to move a north-seeking unit magnet pole from one point to the other point.

Unit of Magnetic Reluctance.—A unit of magnetic reluctance is said to exist between two points when it requires a unit of magnetomotive force to develop one line of magnetic flux.

The Unit of Flux Density.—The unit of flux density is one line of induction per square centimeter.

The Practical Electrical Units are:

The *ampere* which is defined as the unvarying current which, when passed through a standard solution of nitrate of silver in water, will deposit silver at the rate of 1.118 milligrams per second.

The *coulomb* which is defined as the quantity of electricity passing any given point on a conductor in 1 second when 1 ampere is flowing.

The *ohm* which is defined as the resistance offered to an unvarying electric current by a column of mercury of constant cross-section, at the temperature of melting ice, 14.4521 grams mass, and of a length of 106.3 centimeters.

The *volt* which is defined as $\frac{100,000}{101,830}$ of the electromotive force of a Weston normal cell at a temperature of 20°C.

The *henry* which is defined as the inductance of a circuit such that an electromotive force of 1 volt is induced when the current changes at the rate of 1 ampere per second.

The *farad* which is defined as the capacitance of a conductor or system of conductors which will raise the potential of the conductor or conductors 1 volt by a charge of 1 coulomb.

6. The fundamental relation in electric circuits is expressed by Ohm's law; this is:

$$I = \frac{E}{R},$$

or

$$IR = E,$$

or

$$R = \frac{E}{I}.$$

CHAPTER V

TRANSFORMATION OF ENERGY

52. Introduction.—The process of the development and utilization of the electrical current is merely a process of transforming energy from one form into another form, transmitting it by wires to some other place, and there again converting it into usable form. Thus if a direct-current generator be driven by a waterwheel, the energy of the water, through the agency of the wheel and generator, is converted into the energy of the electrical current which may be transmitted by wires to motors, lamps, or some other device which again transforms the energy into heat and light as in the lamp, or mechanical energy as in the motor. The subject of energy and its transformation is thus very important in the study of electrical machinery.

53. Work.—Every one has some notion of the meaning of the word "work." We say that a man has worked hard when he has spent much mental effort in solving some problem. Likewise we say a hod-carrier works hard when he carries bricks or mortar from the ground to the top of a building. The two cases are, however, evidently not the same. The degree of fatigue resulting may be the same, but it is plainly not like in kind. There is no way of physically measuring the mental effort, while the measure of the physical effort of the hod-carrier is the number of bricks and the elevation to which he has carried them. In mechanics the meaning of work is restricted and has reference solely to physical quantities.

In the second illustration there are two factors that cause the fatigue of the hod-carrier: one is the force he must exert to raise the bricks, and the other is the distance through which he carries them. The work done thus contains the two elements, force and distance. Work, therefore, is that which is accomplished by a force acting through a distance and is measured by the product of the intensity of the force and the distance through which the force acts. Algebraically this is expressed by

$$\text{Work, } W = Fd \cos \alpha,$$

where α is the angle between the direction of motion and the direction of the force, Fig. 44. $F \cos \alpha$ is the component of the force in the direction OM. If the body moves in the direction of the force $\alpha = 0$ and we have

$$W = Fd.$$

It is worth noting that time does not enter into work. Work is merely the accumulated result, and the time required to accomplish it is not considered.

54. Unit of Work.—In the English system of units, the unit of work is the *foot-pound* and is represented by the quantity of work done in raising a pound weight 1 foot against the force of gravity. In the metric system, the unit of work is called the *erg* and is the quantity of work done by a force of 1 dyne acting through a distance of 1 centimeter. The erg is a very small quantity and

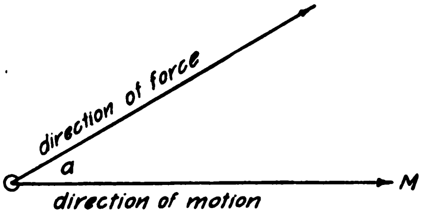


FIG. 44.

hence 10,000,000 (= 10^7) ergs are taken as the practical unit. The practical unit is called the *joule,* and 3,600,000 joules are equal to 1 *kilowatt-hour.* The kilowatt-hour is extensively used in electrical calculations.

55. Relation between English and Metric Units of Work.—The unit of force in the metric system is the *dyne.* The dyne has been defined, Article 34.

In the English system of units the unit of force is the pound. It is the pull of gravity upon a pound mass. Thus a pound force is capable of giving an acceleration of 32.2 feet per second per second to a pound mass.

As the pound mass = 453.59 grams mass

$$\begin{aligned} \text{1 pound force} &= 32.2 \times 30.48 \times 453.59 \text{ dynes} \\ &= 445{,}000 \text{ dynes, approximately} \\ \text{1 foot-pound} &= 1 \text{ pound} \times 1 \text{ foot} \\ &= 445{,}000 \times 30.48 \text{ ergs} \\ &= 13{,}563{,}600 \text{ ergs.} \end{aligned}$$

But 10,000,000 ergs = 1 joule.
Hence 1 foot-pound = 13,563,600 ÷ 10^7 = 1.356 joules.

Examples

1. The diameter of the cylinder of a steam engine is 24 inches. The piston moves a distance of 24 inches at each stroke. What work in foot-pounds will be done at each stroke if the average steam pressure is 125 pounds per square inch?

Solution.—

$$\text{Work} = Fd$$
$$F = \text{total pressure on the piston}$$
$$= \pi \times 12^2 \times 125$$
$$d = 24 \div 12 = 2 \text{ feet.}$$

Hence

$$W = 2 \times \pi \times 12^2 \times 125$$
$$= 113{,}098 \text{ foot-pounds.}$$

2. How many joules, and how many kilowatt-hours of work will be done at each stroke of the piston mentioned in example 1?

Solution.—

1 foot-pound = 1.356 joules.
Hence 113,098 foot-pounds = 113,098 × 1.356
= 153,361 joules
1 kilowatt-hour = 3,600,000 joules.
Hence 153,361 joules = 153,361 ÷ 3,600,000
= 0.0426 kilowatt-hours.

56. Energy.—Energy and work are closely related. When a body has been lifted to a certain height, a definite amount of work has been done upon it. This work in foot-pounds is equal to the product of the height in feet by weight in pounds. The body, when elevated, possesses something which it does not possess at a lower level. Again, water at the top of Niagara Falls is capable of doing work by being run through a waterwheel. When it leaves the waterwheel and enters the river at the bottom of the falls, it is no longer capable of doing work. That is, it has parted with its ability to do work in descending from the top to the bottom of the falls. The energy of a body or a system of bodies is its capacity for doing work. It is measured by the work which can be performed.

Energy is classified under two heads *potential* and *kinetic*. The energy that a body possesses by virtue of its position is called *potential*. Thus, the water at the top of the falls is capable of doing work on descending to a lower level. It thus possesses

energy of position. Similarly, a body lifted to a given height possesses energy of position. If the body be dropped, the elevation will decrease, but its energy will not decrease until it strikes the earth and transfers its energy to some other body. When only a short distance, say 1 inch, from the lowest point in its fall, its energy of position is very small, and just before it strikes, the energy of position is practically zero. The velocity of the body is maximum or greatest at the time of striking, and zero at its highest point. The total energy of the body thus consists of energy of position and energy of motion. The energy due to the velocity of the body is called *kinetic*. The simple pendulum will help make this clear. The simple pendulum at the extreme position of its swing, A, Fig. 45, possesses energy due to its elevation.

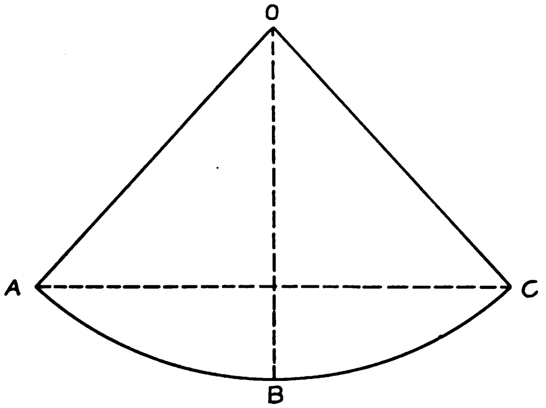


FIG. 45.

When released, this elevation decreases until the pendulum reaches the lowest point, B, of its swing when its elevation is zero, but its velocity is a maximum. The potential energy has all been changed to kinetic. As the pendulum passes beyond the middle point of its swing, the velocity decreases, hence its kinetic energy decreases; the elevation of the pendulum increases and, therefore, the potential energy increases. This change continues until the pendulum reaches the other extremity, C, of its swing, when the energy is again wholly potential. The sum total of the energy of the pendulum is constant at any point of the swing. That is, the sum of its kinetic and potential energy is a constant quantity.

As already stated, the unit of energy is the same as the unit of

work, and the energy of a body is equal to the amount of work expended upon the body. This is a simple statement of the fundamental principles of dynamics, viz., the principle of the conservation of energy. Newton limited his laws to motion. In reality this third law may be considered as applying to energy as well. Thus, the statement "action is equal to reaction" is also true with reference to the expenditure of energy. No body is capable of doing work unless work is first done upon it. All machines act simply as means of transferring energy from one system to another system. The full appreciation of this principle is of comparatively recent date. Perhaps the most important discovery in the realm of mechanics is the following: *The sum of kinetic and potential energies of a body or system of bodies is a constant quantity, unless it be changed by some external influence.* In other words, the energy of a system cannot be created or annihilated. No human being can create or destroy energy. A distinction must, however, be made between the total amount of energy of a body or system of bodies, and the amount of energy that the system is capable of transferring to another system. In all mechanical operations some energy is dissipated or wasted or becomes unavailable. For instance, a simple pendulum released at the extreme position of its swing, will not of itself reach the same point on its return. This is due to the fact that some of its energy has been transferred to the air, and another portion has been dissipated on account of the friction and stiffness of the string supporting it, etc. Similarly some of the energy delivered by a steam engine to an electric generator is wasted in friction of the air, at the bearings, brushes, etc. The law of the conservation of energy is fundamental in all energy transformations.

57. Power.—In everyday usage, the word power has many different meanings. It is often confused with work. Power is not work, but the time rate of doing work. As an illustration suppose that one man carries 2,000 bricks to the second story of a building in 1 day while it takes another man 2 days to do the same work. Evidently, the total amount of work done in the two cases is the same although the rate at which the work is done is different. The second man's rate of doing the work is only one-half that of the first man's rate. Technically, this is explained by saying that the powers of the two men are different. The power of the first man is double that of the second man. Power is then the amount of work done in some unit of time. In engineering

practice the unit of time is usually the minute or second. In algebraic symbols power is expressed by

$$\text{Power, } P = \frac{\text{work}}{\text{time}} = \frac{W}{t}$$

$$= \frac{F \times d}{t},$$

or

$$P \times t = F \times d = \text{work}.$$

58. Units of Power.—In the British system of units, the unit of power is the rate of doing 33,000 foot-pounds of work in 1 minute. This unit is called the *horsepower*. In the metric system the corresponding unit is the *kilowatt*. The *kilowatt* is the rate of doing 1,000 joules per second. One joule per second is called the *watt*.

It has been shown that 1 foot-pound equals 1.356 joules; therefore, 33,000 foot-pounds equal 33,000 × 1.356 = 44,748 joules, and, one horsepower equals 44,748 joules per minute. One kilowatt equals 60,000 joules per minute, hence

$$1 \text{ hp.} = \frac{44{,}748}{60{,}000} = 0.746 \text{ kilowatt}$$

$$= 746 \text{ watts}.$$

Approximately, 1 horsepower equals ¾ kilowatt, or conversely 1 kilowatt equals 4/3 horsepower. A knowledge of these relations is useful and they should be remembered.

Examples

1. How much energy is stored in a tank of water containing 1,000,000 gallons if the average height to which the water has been pumped is 100 feet?

Solution.—One gallon of water weighs about 8.35 pounds. 1,000,000 gallons weigh 1,000,000 × 8.35 = 8,350,000 pounds. To raise 8,350,000 pounds of water 100 feet high will require an expenditure of energy of 8,350,000 × 100 = 835,000,000 foot-pounds. This is the stored or potential energy of the water.

2. What must be the horsepower of an engine to pump the water in question 1, in 5 hours?

Solution.—One horsepower = 33,000 foot-pounds per minute. In 1 hour an engine of 1 horsepower will perform

33,000 × 60 = 1,980,000 foot-pounds.

In 5 hours it will do 5 × 1,980,000 = 9,900,000 foot-pounds. To do 835,000,000 foot-pounds will require 835,000,000 ÷ 9,900,000 = 84+ horsepower.

3. If an electric motor were used in place of the engine, what would its rating be in kilowatts (neglecting losses)?

Solution.—One horsepower = 746 watts

$$= 0.746 \text{ kilowatts.}$$

Hence

$$84 \text{ horsepower} = 84 \times 0.746 = 62.66 \text{ or } 63 \text{ kilowatts.}$$

59. Electricity and Electrical Energy.—It is impossible at present to explain electricity in terms of anything more elemental than itself. We know electricity only through its manifestations or effects. It matters not, so far as practical results are concerned, whether electricity is a form of energy or only a vehicle of energy. The fact is that energy is always manifest in connection with the electrical current, and that this energy can be transformed into other forms of energy. It may also be transferred from point to point along a conductor without the necessity of mass motion. It is this ability to transfer energy without the motion of masses of matter that makes electricity the most successful medium for transferring energy over long distances. The transformation of electrical energy is electrical work and is accomplished in many ways. The rate of transformation is power just as in the case of other forms of energy.

60. Electrical Work.—The derivation of the principles of electrical work or energy will undoubtedly be better understood if analogies are used. The quantity of water flowing through any pipe in a given time may be expressed as the strength of current multiplied by the time. A unit current of water has no name. If a unit current gives a cubic foot (62.3 pounds) of water in 1 second, a two-unit current will give 2 cubic feet of water per second or 10 cubic feet in 5 seconds.

Similarly, a unit current of electricity flowing for 1 second gives a definite quantity of electricity. This quantity is called the coulomb. The total quantity conveyed by a constant current of I amperes in t seconds is then given by $Q = It$. Again, referring to the analogy of water flowing through pipes one may consider unit work to be done when 1 cubic foot of water is delivered under a head of 1 foot. The amount of work done by a head of h feet, delivering q cubic foot of water will be hq. But electrical pressure is analogous to water pressure, or head; and the quantity of water is analogous to the quantity of electricity or coulombs. A current delivering Q coulombs of electricity under a pressure of

E volts will then do EQ units of work. This may be expressed algebraically, thus:

$$\text{Work} = E\ (\text{volts}) \times Q\ (\text{coulombs})$$
$$= EQ\ \text{joules.}$$

The relations between volts, coulombs, and joules are such that the product of 1 volt by 1 coulomb gives 1 joule. It has been shown, however, that Q, the quantity, is equal to It, the current by the time. We may then write the expression for work thus:

$$\text{Work, } W = EIt.$$

When E is in volts, I in amperes and t in seconds, the result is in joules. If t is 1 second, we have

$$W = EI \text{ joules per second.}$$

One joule per second is 1 watt, hence in direct-current calculations, volts × amperes gives watts. In electrical work the joule is a small unit of energy so 1,000 watts for 1 hour is usually used. This unit is called the *kilowatt-hour.*

Examples

1. What power is being developed by a direct-current generator when it is delivering 84 amperes under a pressure of 250 volts?

Solution.—

$$\text{Power in watts} = \text{volts} \times \text{amperes}$$
$$= I \times E$$
$$I = 84 \text{ amperes}$$
$$E = 250 \text{ volts.}$$

Hence $$P = 250 \times 84 = 21{,}000 \text{ watts}$$
$$1{,}000 \text{ watts} = 1 \text{ kw.}$$

Then $$P_{kw} = 21{,}000 \div 1{,}000 = 21 \text{ kw.}$$

2. An electric heater takes 7.5 amperes at a pressure of 110 volts. How much will it cost to operate the heater for 1 month, 30 days, if it is operated on an average of 8 hours per day, at 5 cents per kilowatt-hour?

Solution.—

$$\text{Energy consumed} = \frac{IEt}{1{,}000} \text{ kilowatt-hours}$$
$$I = 7.5 \text{ amperes}$$
$$E = 110 \text{ volts}$$
$$t = 8 \times 30 \text{ hours}$$

$$\text{Hence energy} = \frac{7.5 \times 110 \times 8 \times 30}{1{,}000} = 198 \text{ kilowatt-hours.}$$

$$\text{Cost} = 198 \times 0.05 = \$9.90.$$

3. A direct-current generator supplies energy to a street railway motor. If the pressure at the generator is 550 volts and that at the motor 500 volts, what power is lost on the line when 75 amperes are flowing?

Solution.—The loss in pressure is 50 volts, hence the power lost is

$$75 \times 50 = 3{,}750 \text{ watts}$$
$$= 3.75 \text{ kilowatts.}$$

61. Power Loss.—According to Ohm's law the pressure drop across a resistance R, when a current of I amperes is flowing is $I \times R$ or

$$E = I \times R.$$

If E is the pressure which sends a current of I amperes through the resistance, then the power spent in the resistance is IE watts. Multiplying both sides of $E = IR$ by I we get

$$EI = I^2R.$$

Since IE is the rate at which energy is spent in the resistance, and $IE = I^2R$, then the power loss is equal to I^2R watts. That is, the energy spent per second in forcing a current through a resistance is equal to the square of the current multiplied by the resistance.

Examples

1. The resistance of a shunt field winding of a motor is 40 ohms. What is power loss in the winding when 2 amperes are flowing?

Solution.—

$$P = I^2R$$
$$I = 2 \text{ amperes}$$
$$R = 40 \text{ ohms.}$$

Hence $$P = 4 \times 40 = 160 \text{ watts.}$$

2. A projection lantern is operated on a 110-volt circuit. The resistance of the controlling rheostat is 3.5 ohms. If the voltage drop across the lamp is 50 volts, what current does the lamp take and how much power is lost in the rheostat?

Solution.—The voltage drop across the rheostat, which must be the difference between the drop across the lamp and the supply voltage, is $110 - 50 = 60$ volts. By Ohm's law,

$$I = \frac{E}{R}$$
$$E = 60$$
$$R = 3.5.$$

Then $$I = \frac{60}{3.5} = 17.1 \text{ amperes.}$$

The power loss is $$I^2R = 17.1 \times 17.1 \times 3.5$$
$$= 1{,}023 \text{ watts, nearly.}$$

3. A transmission line consists of two No. 0 copper wires and is 5 miles long. How much power is wasted in the line when 75 amperes are flowing?

Solution.—

$P = I^2R$

$I = 75$

R = resistance of 10 miles of No. 0 wire

$= 10 \times 0.528 = 5.28$ ohms (resistance of No. 0 wire = 0.528 ohm per mile).

Then $P = 75^2 \times 5.28$

$= 29{,}700$ watts

$= 29.7$ kilowatts.

62. Heating Value of the Electric Current.—The power loss in a conductor is given by I^2R. This is all converted into heat and the exact relation was first determined by James Prescott Joule, an English physicist. He did this by immersing a conductor of known resistance into a known weight of water and measuring the current, time, and temperature. The results of his experiments show that the heat generated in a conductor is proportional to the time the current flows, to the resistance, and to the square of the current. This condition may be written in algebraic form as follows:

$$\text{Heat} = KI^2Rt.$$

This is evidently the energy loss in a conductor multiplied by a conversion factor K. This factor is introduced on account of the fact that the unit for the measurement of heat is not the same as that for the measurement of electrical energy. The unit for heat measurement is the quantity of heat required to raise the temperature of 1 gram of water from 15° to 16°C., and is called a calorie. The calorie is equal to 4.181 joules. That is, the heat unit is 4.181 times the electrical unit. To convert joules to calories we must multiply the joules by $\frac{1}{4.181} = 0.24$. This 0.24 is the constant K which we can replace and get

$$\text{Heat, in calories,} = 0.24I^2Rt,$$

where I is in amperes, R in ohms, and t in seconds.

The mechanical engineering unit of heat is called the British thermal unit, which is abbreviated to B.t.u. A B.t.u. is the heat required to change the temperature of 1 pound of water 1 degree Fahrenheit. One B.t.u. = 252 calories.

Examples

1. How many calories of heat per hour are developed in an electric heater which takes 7.5 amperes at 110 volts pressure?

Solution.—

$$\text{Heat in calories} = 0.24I^2Rt$$
$$= 0.24EIt$$
$$I = 7.5 \text{ amperes}$$
$$E = 110 \text{ volts}$$
$$t = 3{,}600 \text{ seconds.}$$

Hence,
$$\text{Heat} = 0.24 \times 7.5 \times 110 \times 3{,}600$$
$$= 712{,}800 \text{ calories.}$$

63. Conversion of Mechanical into Electrical Energy.—In Article 52 it was pointed out that the development of an electric

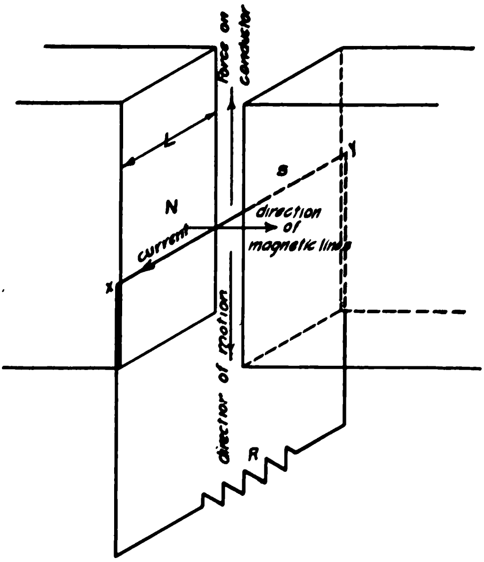


FIG. 46.

current is merely a process of transformation of energy. Then in Article 56 it was shown that no energy can be mechanically transferred or transformed, unless there is a reaction between the different parts of the system.

Thus the kinetic energy of the steam is transferred to the piston of the engine only if the piston reacts or pushes against the pressure of the steam. Likewise no energy can be stored in the flywheel unless the flywheel reacts against the driving force. This principle has many applications.

In Fig. 46, if the conductor be moved across the magnetic field at a uniform rate a constant electromotive force will be induced in it. It has been shown that the electromotive force induced depends upon the rate of cutting the magnetic lines. When the circuit is closed a current will flow in accordance with Ohm's law. It has, however, just been shown that the product of EIt is energy. Hence, when a current flows in the conductor, some energy is being transferred to the conductor. Where did this energy come from? If the circuit is left open, an electromotive force is induced but no current flows, hence no energy is being transformed. If an experiment is performed to test the matter it will be found that it requires more effort to force the conductor across the field when the circuit is closed than when it is opened. The energy must come from the agent driving the conductor across the field, and there is a reaction against the driving force when the circuit is closed and no reaction when it is opened. The amount or value of this reaction may be determined in accordance with principles already established.

It was shown in Article 19 that a force is exerted upon a current-carrying wire by a magnetic field, and that the value of this force is

$$F = IBl \text{ dynes,}$$

when I, B, and l are measured in absolute units.

This force must be overcome in moving the conductor across the magnetic field. If V is the speed at which the conductor is moved, then $FV = IBlV$ is the power developed in the conductor.

It has also been shown that BlV is the electromotive force developed. Hence $FV = IE$.

When I is given in amperes and E in volts, then $FV = \frac{1}{10}I \times E \times 10^8 = I \times E \times 10^7$ ergs per second,

$$FV = IE \text{ joules per second}$$

or

$$= IE \text{ watts.}$$

FV is the mechanical power, and EI is the electrical power developed. The force $F = \frac{IE}{V}$ opposes the motion. If the velocity V changes, the electromotive force E varies directly as V.

Examples

1. What force will be required to move a short-circuited conductor across a magnetic field of 5,000 gausses if the conductor is 100 centimeters long,

moves at a uniform speed of 100 centimeters per second and the circuit has a resistance of 0.04 ohm?

Solution.—

$$F = \frac{IE}{V}$$

$$I = \frac{E}{R}$$

$$E = BlV$$

$$E = 5{,}000 \times 100 \times 100$$

$$= 50{,}000{,}000 \text{ absolute units of pressure}$$

$$I = \frac{50{,}000{,}000}{0.04 \times 10^9}$$

$$= 1.25 \text{ absolute units of current}$$

$$F = \frac{50{,}000{,}000 \times 1.25}{100}$$

$$= 625{,}000 \text{ dynes}$$

$$= \frac{625{,}000}{445{,}000} = 1.4 \text{ pounds.}$$

2. What force will be required to force the conductor across at the rate of 200 centimeters per second?

Solution.—

$$E = 5{,}000 \times 100 \times 200$$

$$I = \frac{5{,}000 \times 100 \times 200}{0.04 \times 10^9} = 2.5 \text{ absolute units}$$

$$F = \frac{5{,}000 \times 100 \times 200 \times 2.5}{200} = 1{,}250{,}000 \text{ dynes}$$

$$= 2.8 \text{ pounds.}$$

The reaction is thus directly proportional to the speed. It must be noted that this is true only so long as the resistance of the circuit and the flux density remain constant.

Recapitulation

1. Work is defined as the product of a force and the displacement produced by *or against* this force in the direction of the force.

(*a*) The unit of work in the English system of units is called a *foot-pound.* The *foot-pound* is the work done in lifting a weight of 1 pound 1 foot high against gravity.

(*b*) In metric units the unit of work is the *joule.* A *joule* is equal to 10,000,000 ergs. An *erg* is the work done by a force of 1 dyne acting through a distance of 1 centimeter.

2. *Energy* is the ability of doing work. The units for measuring energy are the same as those for work.

3. *Power* is the time rate of doing work.

(*a*) The *English* unit of power is the *horsepower.* A *horsepower* is the rate of doing 550 foot-pounds of work per second.

(*b*) The metric unit of power is the *watt.* A *watt* is the rate of doing 1 joule per second. One horsepower = 746 watts. A *kilowatt* = 1,000 watts.

4. Work in direct-current circuits is obtained by multiplying volts by amperes by time. Algebraically it is given by

$$\text{Work} = EIt.$$

The commercial unit for electrical energy or work is the kilowatt-hour. A kilowatt-hour is the work done by 1 kilowatt in 1 hour; it equals 3,600,000 joules.

5. *Power* in direct-current circuits is obtained by multiplying volts by amperes, or

$$\text{Power} = EI \text{ watts.}$$

6. *Power loss* is the loss of energy per second when a current of I amperes flows through a resistance R ohms. It is equal to I^2R watts.

7. A *calorie* is the quantity of heat required to raise the temperature of 1 gram of water from 15° to 16°C. One calorie = 4.181 joules.

A *British thermal unit* is the quantity of heat required to change the temperature of 1 pound of water 1 degree Fahrenheit. One B.t.u. = 252 calories.

The heat generated by a current of I amperes in a resistance of R ohms in time t seconds is given by

$$\begin{aligned} \text{Heat (calories)} &= 0.24I^2Rt \text{ calories} \\ &= 0.24 \text{ watt} \times t. \\ \text{Heat (B.t.u.)} &= 0.00095I^2Rt \\ &= 0.00095 \text{ watt} \times t. \end{aligned}$$

8. When a wire is moved across a magnetic field, there will be developed a reaction against the motion only when a current flows in the wire. By means of this reaction the mechanical energy of the agent moving the wire is converted into electrical energy. The reaction is due to the interaction of the magnetic field inducing the electromotive force and the magnetic field of the resulting current.

CHAPTER VI

THE CONTINUOUS-CURRENT GENERATOR AND MOTOR

64. Introduction.—The student has now learned that whenever a wire is cut by, or cuts across, a magnetic field, an electromotive force is induced or developed in it. It has also been shown that when a wire is short-circuited or connected in such a manner that a current can flow, a force must be exerted to move it across a magnetic field, or in other words, the process of generating an electrical current is merely a process of the conversion of energy. A machine which is used for converting mechanical energy into electrical energy is called an *electrical generator*, or sometimes a *dynamo*. The former appellation is preferable, for the word dynamo has a more general meaning and includes machines which also convert electrical energy into mechanical energy, that is, *motors*.

65. A Continuous-current Generator—commonly called a *direct-current generator*—is a machine which produces at the brush terminals a continuous or unidirectional electromotive force by the rotation of one or more conductors in a magnetic field.

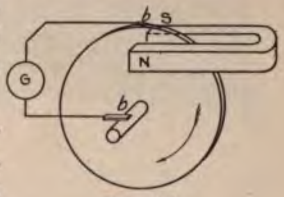


FIG. 47.

66. The Faraday Disk Generator.—The first electrical generator was invented by Michael Faraday. The device was extremely simple as is shown by Fig. 47. This simple generator consisted of a disk of copper 12 inches in diameter mounted on a shaft so that it could be rotated. A permanent magnet was placed with its poles on opposite sides of the disk and near its edge. When the disk was rotated each radius cut the magnetic flux which penetrated the disk in passing from the N-pole to the S-pole of the magnet. This cutting of the magnetic lines induced an electromotive force which, when the circuit was closed, sent a current from the shaft outward as indicated by the arrow. This same principle is used today in the retardation disk of watt-hour meters, Fig. 48.

For many self-evident reasons, the Faraday disk generator was not capable of developing any considerable pressure; it was important, however, as it led to the development of other forms which were better adapted for the generation of higher pressures.

67. The Elements of a Generator.—As has been pointed out, the necessary elements of a machine for the generation of an electromotive force are a magnetic field and a conductor or conductors which can be caused to move across the field. The conductors in which an electromotive force is induced are usually called inductors, a term we shall hereafter employ. The simplest form of such a machine is shown in Fig. 49. A loop of wire is mounted on a shaft so that it can be rotated on its axis and made to cut through the magnet flux passing from the N-pole to the S-pole. At the instant when the plane of the loop is in the vertical position, as shown

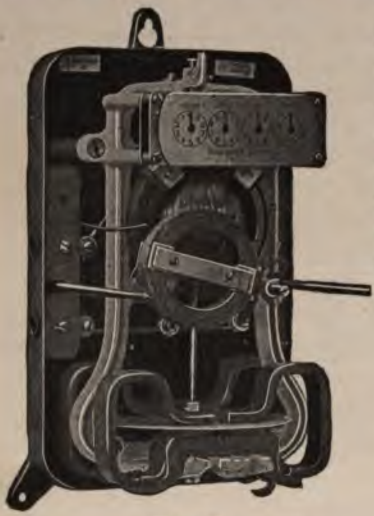


FIG. 48.

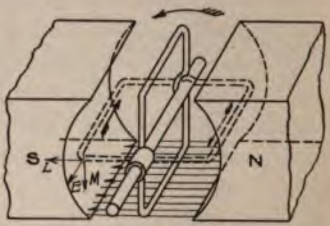


FIG. 49.

by the full lines, the inductors are moving parallel to the lines of magnetism; no magnetic lines are being cut and, hence, no electromotive force is induced.

When the plane of the loop is in the horizontal position, as shown by the dotted lines, the inductors are moving at right angles to the flux; the rate of cutting the magnetic lines is a maximum and the pressure induced is also a maximum.

68. Direction of Induced Electromotive Force.—When the inductors are rotated in the direction indicated in the figure, the direction of the induced pressure is from front to back in the left side of the loop, and from back to front in the right side of the loop. These directions are indicated by arrows near the inductors. The application of Fleming's right-hand rule will enable

the student to verify this. The electromotive forces in the two sides of the loop will tend to cause a current to flow in the same direction around the loop and the electrical pressure, between the ends of the loop, will be the sum of the pressures induced in each of the two inductors, or sides of the loop.

When the plane of the inductors is rotated one-quarter of a rotation farther, it will again be in a vertical position, but the position of the inductors will be interchanged; the inductor which was at the top in the first instance is now at the bottom, and *vice versa.* As the loop passes this point it again begins to cut the magnetic flux, and an electromotive force will be induced in the inductors, but as the position of the inductors has been interchanged, the electromotive force will be reversed with reference to that of the first half rotation; that is, the direction of the in-

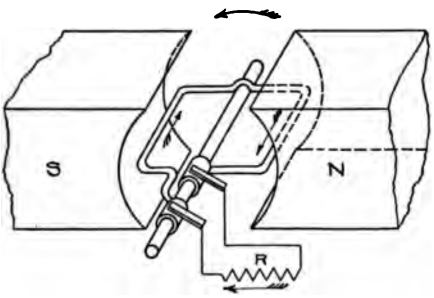


Fig. 50.

duced electromotive force and of the resulting current is reversed every time the inductors turn through an angle of 180°, measuring from the vertical position. If two rings be attached to the loop, one being connected to each end, and the two rings be mounted so as to rotate with the shaft, the pressure between these rings will reverse every time the loop passes through the vertical position, or every time it makes one-half rotation measuring from the vertical position. Current can be taken from these rings by placing a brush on each, as shown in Fig. 50, and connecting them to a conducting circuit.

Since the direction of the induced electromotive force reverses every one-half revolution, the flow of current in the circuit will be correspondingly reversed, that is, an alternating current will flow in the circuit. This changing of current from zero to a maximum value, then decreasing to zero, reversing, building up to a

maximum value in the opposite direction and then decreasing to zero again is shown in Fig. 51.

When the plane of the inductors is in a vertical position, as shown by the full lines, Fig. 49, the pressure is zero corresponding to point A, Fig. 51.

69. Fluctuation of Induced Electromotive Force.—In Article 30 it was shown that the electromotive force induced in a conductor at any instant is given by $e = Blv \sin \theta$, where θ is the angle the plane of the conductor makes with the plane normal, or at right angles, to the magnetic flux. This is the same as the angle the direction of motion makes with the direction of the magnetic lines.

The quantity Blv is constant, assuming constant speed of rotation, hence the induced electromotive force varies as the sine of

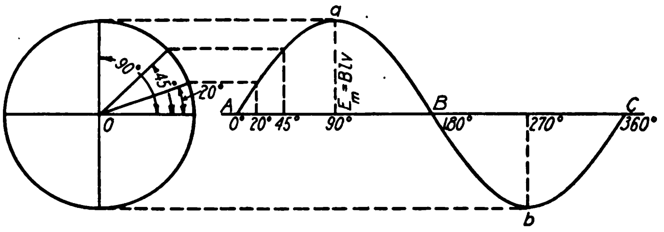


FIG. 51.

the angle the direction of motion of the inductor makes with the direction of the magnetic lines, or the sine of the angle the plane of the inductors makes with the plane normal to the magnetic field. The induced electromotive force is thus a periodic quantity. We may represent the variations in the induced electromotive force graphically. If in Fig. 51 we let AC represent 360° of arc, or the angle described by the rotating inductors in one rotation, one-eighteenth of AC will represent an angle of 20°, one-eighth of AC will represent an angle of 45°, one-fourth of AC an angle of 90°, one-half of AC an angle of 180°, etc. These points are marked 20°, 45°, 90°, 180°, 270°, and 360°, respectively, in the diagram. If at these points of division we draw vertical lines proportional to $Blv \sin \theta$ for that particular value of θ, this vertical line will represent the induced electromotive force at that instant. As

$$e = Blv \sin \theta$$

when $\theta = 0$, $\sin \theta = 0$, and

$$e = 0,$$

This is the point A, zero distance above AC.

When $\theta = 20°$, $\sin\theta = 0.324$ and $e = 0.324Blv$.

At the point on AC marked 20° we erect a line proportional to $0.324Blv$; we get a line which represents the magnitude of the induced pressure at that instant. In the same way when $\theta = 45°$, $\sin\theta = 0.707$, and $e = 0.707Blv$, and the vertical line at the point marked 45° represents the electromotive force induced in the inductors when they have made one-eighth of a rotation. When the inductors have made one-fourth of a rotation $\theta = 90°$, $\sin\theta = 1$, and $e = Blv$. This is the maximum value that the pressure can attain, hence we may replace Blv by E_m, where E_m represents the maximum electromotive force, and the line drawn from the point 90° to a represents this maximum pressure. Our general expression for the instantaneous pressure then becomes

$$e = E_m \sin\theta.$$

As θ is a uniformly varying angle, we can replace it by ωt where ω is the angle described by the inductor in 1 second, and t is the number of seconds that have elapsed since the plane of the conductors passed through the vertical position. Replacing θ by ωt we have

$$e = E_m \sin\omega t$$

which is the most common expression for the instantaneous electromotive force.

When $\omega t = 0°$	$e = 0$
When $\omega t = 20°$	$e = 0.324E_m$
When $\omega t = 45°$	$e = 0.707E_m$
When $\omega t = 90°$	$e = E_m$
When $\omega t = 180°$	$e = 0$
When $\omega t = 270°$	$e = -E_m$
etc.	etc.

As the inductors revolve through an angle greater than 90°, the value of $\sin\omega t$ decreases, hence the lines representing the induced electromotive force will grow shorter and shorter until when one-half revolution has been made the induced electromotive force is again 0. During the second half of the revolution the induced electromotive force will pass through the same values except that in each inductor the pressure will be reversed. As we have plotted the values of the electromotive force for the

first half of a revolution above the line AC, we must plot the values for the second half of a revolution below the line. Joining the extremities of the vertical lines by a smooth curve, we get the curve $AaBDC$, which shows how the induced electromotive force varies in the inductors as they revolve across a uniform magnetic field. In the simple generator just explained the armature is the rotating part of the generator, while the magnetic field is stationary. This is always the case in direct-current or continuous-current machines. It is not always so with alternating-current machines.

70. The Commutator.—We have just seen that when a single loop armature rotates in a magnetic field an alternating electromotive force is induced in the inductors. This is evidently true no matter how many inductors are rotated across the field. Each

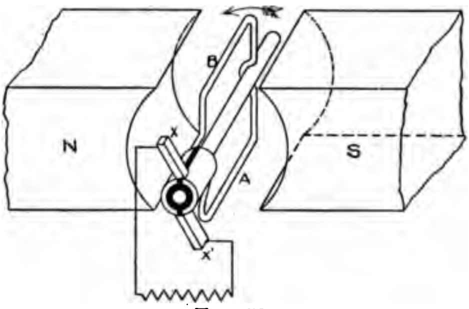


FIG. 52.

and every inductor will have the electromotive force induced in it reversed every time it passes from under one pole and begins to cut across the flux under a pole of opposite polarity. In order to deliver a continuous, or unidirectional current to a receiving circuit, such as lamps or motors, it is necessary to commutate or reverse the direction of the armature current every time the electromotive force is reversed. This is done by interchanging the connections of the armature inductors with the external, or receiving, circuit every time the electromotive force in the inductors is reversed. The device used for interchanging the connections is called a *commutator*. A simple device for commutating the current from a single loop armature may be made by cutting in halves a short piece of brass or copper tubing and mounting the two pieces on the shaft of the loop. The two parts of the commutator are insulated from each other, and from the

shaft; one end of the loop is connected to each half. Two brushes are placed diametrically opposite on the commutator and set in such a position that the parts of the commutator will pass from one brush to the other at the instant the pressure is zero. The arrangement of these parts is shown in Fig. 52.

With the coil in the vertical position, as shown, there is no pressure induced and hence there will be little or no sparking as the commutator parts or segments move from one brush to the

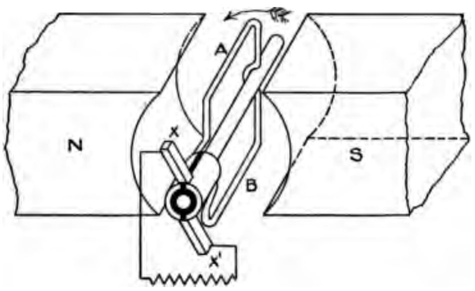


FIG. 53.

other. During the first half revolution from this position current will flow through the loop from front to back in A, and back to front in B, toward the top brush X, through the external circuit to X' and through the loop from X' to X. When the loop starts the second half revolution, the segments of the commutator have passed under different brushes. The conductors A and B will be in the position shown in Fig. 53 or interchanged from that of Fig. 52. The current will flow through the loop from front to

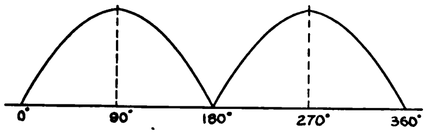


FIG. 54.

back in B and from back to front in A, and to the top brush X. That is, the direction of current in the loop is reversed but the segments have changed contact from one brush to the other so the current flows in each of the above cases to the same brush X. The brush X is the positive brush and the current flows in the external circuit from X to X', although it reverses in the loop A–B. This device will, by means of the inductors, commutator,

and brushes, give a flow of current in one direction through the external circuit, but the current will vary in value from zero to a maximum and fall to zero, twice in each revolution of the loop in a two-pole field, that is, the current will be unidirectional but pulsating, Fig. 54.

71. The Value of an Electromotive Force Induced in a Single-loop Armature.—It has been shown, Art. 29, that the average pressure induced in an inductor as it cuts across a flux Φ is equal to the rate at which the flux is cut. Algebraically

$$E = \frac{\Phi}{t \times 10^8} \text{ volts.}$$

If, in Fig. 52 or 53, a flux Φ extends from the N- to the S-pole through the armature, and if the armature makes n rotations per minute, then each inductor will cut the flux twice in one rotation. In n rotations each inductor will cut the flux $2n$ times. Hence, in each inductor there will be induced a pressure

$$E = \frac{2n\Phi}{60 \times 10^8} \text{ volts.}$$

As the two inductors are connected in series, the total voltage will be twice that induced in one inductor. Hence, the pressure between the brushes will be

$$E = \frac{2 \times 2n\Phi}{60 \times 10^8} \text{ volts.}$$

In general if there are Z inductors connected in series the voltage between the brushes for a two-pole generator is given by the expression

$$E = \frac{2nZ\Phi}{60 \times 10^8} \text{ volts.}$$

Examples

1. Assume the cross-sectional area of the poles in Fig. 49 to be 800 square centimeters, and that the flux density is 5,000 lines of induction per square centimeter. What is the pressure between the brushes when the single loop armature makes 3,600 rotations per minute?

Solution.—

$$E = \frac{2nZ\Phi}{60 \times 10^8} \text{ volts}$$

$$n = 3{,}600$$

$$Z = 2$$

$$\Phi = 5{,}000 \times 800 = 4{,}000{,}000 = 4 \times 10^6 \text{ maxwells.}$$

Then $$E = \frac{4 \times 10^6 \times 3{,}600 \times 2 \times 2}{60 \times 10^8}$$
$$= 9.6 \text{ volts.}$$

2. How many inductors will have to be connected in series if the electromotive force in question 1 is to be 48 volts?

Solution.—Two inductors in series generate 9.6 volts. Hence one inductor generates 4.8 volts. To generate 48 volts will require $48 \div 4.8 = 10$ inductors, or a loop of 5 turns.

72. Electromotive Force of a Multipolar Generator.—It will be shown later that the number of parallel circuits in a dynamo armature is determined by the character or kind of winding used. This amounts to the same thing as to say that the number of inductors connected in series is determined by the kind of armature winding employed. If the total number of inductors is Z and there are q paths in parallel, the number of inductors in series is $\frac{Z}{q}$.

Let p = number of field poles,
q = number of parallel circuits in armature winding,
Z = number of inductors,
n = number of revolutions of armature per minute,
Φ = the total flux emanating from one pole.

Then $$E = \frac{pn\Phi Z}{q60 \times 10^8} \text{ volts.}$$

It is plainly evident that the electromotive force of any generator can be varied by changing n, or Φ.

Example

A six-pole generator operating at a speed of 900 revolutions per minute has 960 inductors on the armature. What will be the electromotive force developed if a two-circuit winding is used and if the flux emanating from one pole is 1,200,000 lines?

Solution.—

$$E = \frac{p\Phi Zn}{q60 \times 10^8}$$
$$p = 6$$
$$q = 2$$
$$\Phi = 1{,}200{,}000 = 1.2 \times 10^6$$
$$n = 900$$
$$Z = 960$$

Then $$E = \frac{6 \times 1.2 \times 10^6 \times 960 \times 900}{2 \times 60 \times 10^8}$$
$$= 518 \text{ volts.}$$

73. Electric and Magnetic Principles of the Direct-current Motor.—The method of generation of an electromotive force has been explained. It remains now to show how the energy possessed by an electric current may be utilized in doing mechanical work.

Electrically considered, the direct-current generator and motor are similar machines. Their difference lies in the method of operation. In the case of the generator, mechanical energy is converted into the energy of the electrical current by means of conductors cutting magnetic flux. The process is one of energy transformation. Electrical energy can be converted into mechanical work by a reversal of this process, and by means of the same machine. This is accomplished by supplying electrical energy from some outside source to the machine which is thereby

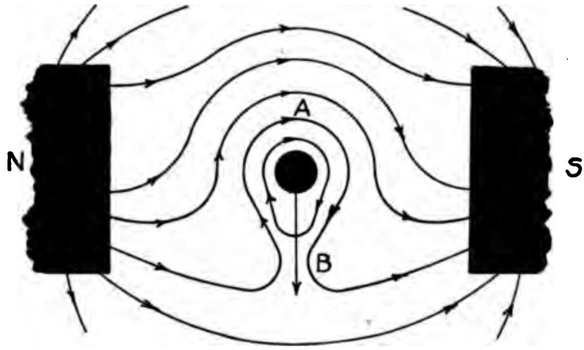


FIG. 55.

converted into a motor. The general laws governing one are the same for the other. In a generator the current flows under the electromotive force induced in the armature conductors. It has been shown that when a current is flowing in the inductors a force is required to move the inductor across the magnetic field. This force has been shown to equal IE/V (see Chapter V). Since action is equal to reaction, there must be a counter force of the same magnitude tending to rotate the armature in the opposite direction. How this force is developed will be readily understood from a consideration of Fig. 55, which shows a current carrying wire at right angles to a magnetic field. The current is assumed to be supplied from some outside source and to be flowing in the conductor away from the observer; that is, into the paper. In the region A, above the conductor, both the lines due

to the magnetic field and those due to the current have the same direction, that is, from left to right. Below the conductor the lines due to the current oppose those emanating from the poles N and S and hence in the region B there will be fewer magnetic lines than in the region A. The tension along the lines, in the region A, will exert a downward force on the conductor.

Fig. 55 shows one conductor between two opposite magnet poles. An exactly similar action will take place if the conductor is one side of a loop or armature coil, Fig. 56. That portion of the loop in which the current flows away from the observer will be forced downward, while the other part is forced upward. The loop, if free to move, will rotate clockwise. If the two ends of the loop be connected to a two-part commutator, Fig. 52, so that the current is reversed when the plane of the loop is in the vertical position, the direction of the force on each half of the loop will also

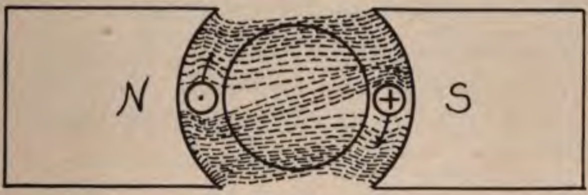


FIG. 56.

be reversed and hence the tendency to rotate will be continuously in one direction.

If the loop of one turn were stopped with its plane in the vertical position, its tendency to rotate will be zero, for no magnetic flux, other than that due to the current in the conductor, is present. When in this position no torque or turning movement is exerted on a single-loop coil. The torque on a single loop will increase from zero to a certain maximum value when the loop is in a horizontal position and then again, decrease to zero. To secure constant torque, the armature is wound with many coils, some of which are always under the field poles. An electric motor does not have a "dead center."

74. Counter Electromotive Force.—In order to understand the interactions of the magnetic and electric quantities, it is desirable first to study the counter electromotive force developed as the armature rotates.

While discussing the principles of generating an electromotive force, we learned that whenever a conductor is moved across a

magnetic field an electromotive force is induced in it; the conductors on the armature of a motor cut magnetic lines when the armature is in motion in precisely the same way as the conductors of a generator, hence, an electromotive force must be induced in them. The direction of this electromotive force must be opposed to that supplied, as will presently appear.

Neglecting small iron losses, the energy applied to a motor is utilized by the motor in two ways; partly in heating the windings, and partly in mechanical work. The part which depends upon the resistance of the windings, and which is dissipated as heat, is proportional to the square of the current and the first power of the resistance, as has already been shown.

Algebraically, energy converted into heat per second $= I^2R$.

The part converted into mechanical work is proportional to the first power of the current and may be expressed as follows:

$$\text{Mechanical energy} = AI,$$

where A is a proportionality factor whose nature is to be determined. According to the law of conservation of energy, the total energy supplied must be equal to that dissipated as heat plus that utilized in work, hence,

$$EI = AI + I^2R.$$

Solving for I, we get

$$I = \frac{E - A}{R}.$$

This expression is in the form of Ohm's law and A must be an electromotive force. Furthermore, this electromotive must be a counter electromotive force, for it is subtracted from the applied electromotive force.

Perhaps another way of looking at the problem will make the matter clearer. When the armature of the motor is at rest and an electrical pressure is applied to its terminals, the current resulting is determined by Ohm's law. If E is the applied pressure and R_a the resistance of the armature circuit, then

$$I_a = \frac{E}{R_a}.$$

The torque or turning moment is proportional to the armature current. If we let T equal the torque, we may write

$$T = KI_a.$$

As soon as the armature begins to rotate, the armature conductors

begin to cut across the magnetic field flux and consequently an electromotive force must be induced in them. The question is, does this induced electromotive force oppose or assist the applied electromotive force? Let us assume that the induced electromotive force is in the same direction as the applied electromotive force. If that be the case, the current I_a will increase, or by Ohm's law I_a will equal $\frac{E + E'}{R_a}$ where E' is the motor electromotive force. Increasing I_a the torque will increase. An increase in the torque will increase the speed, and an increase in speed will increase the motor pressure E'. As a result, the motor will develop an infinite torque and be capable of doing infinite amount of work without receiving a corresponding amount of energy from some outside source. This result is plainly contrary to the law of conservation of energy and hence is untenable. As a matter of fact, the current input in a motor decreases with the speed of the armature. This decrease in current can be due to only one thing and that is, an increasing counter electromotive force with increase in speed.

The value of this counter pressure may be calculated in exactly the same way as the electromotive force of a generator. In general, if

p = number of field poles,
q = number of parallel circuits in the armatures,
Z = number of active inductors,
Φ = magnetic flux issuing from one field pole,
and n = number of rotations of armature per minute,

then $E' = \frac{p \Phi Z n}{q 60 \times 10^8}$ volts, where E' is the motor counter electromotive force.

75. Motor Armature Current.—Having derived an expression for the counter electromotive force of a motor, the expression for armature current may at once be written. Thus if E is the applied pressure and E' the back or counter pressure, then $E - E'$ is the active electromotive force which causes the current to flow through the armature windings. If R_a is the armature circuit resistance

$$I_a = \frac{E - E'}{R_a}.$$

$$= \frac{E - \frac{p \Phi Z n}{q\, 60 \times 10^8}}{R_a}$$

For any given motor $\frac{p\,Z}{q\,60 \times 10^8}$ is constant. Representing this by k we may write

$$I_a = \frac{E - k\,\Phi\,n}{R_a}.$$

This equation is of interest and importance for it shows that the armature current does not depend only upon E and R_a but that it decreases with an increase in Φ or n.

76. Equation for Motor Torque.—By torque is meant the product of the pull in pounds on the belt at the circumference of the motor pulley by the radius of the pulley in inches; thus if the pull is 40 pounds and the radius of the pulley is 6 inches, the torque is 240 pound-inches. For constant-speed motors, the torque is a measure of the power of the motor. This torque is due to the interaction of two magnetic fields; that due to the current in the armature coils, and that due to the current in the field windings.

In Article 63 it was shown that neglecting friction, the power required to rotate the armature of a generator is

$$FV = IE \text{ watts.}$$

In this expression I is the armature current, and E is the induced electromotive force. The power developed by a motor is also given by this expression if for E we substitute the counter pressure which for a motor corresponds to E for a generator. This has been shown to equal $k\Phi n$, where $k = \frac{pZ}{q60 \times 10^8}$. Substituting, we have

$$FV = kI_a\Phi n \text{ watts,}$$

for the power developed by a motor. If T is the torque in pound-inches developed at the motor pulley, and n is the number of rotations per minute, then $2\pi nT$ is the work in inch-pounds developed by the motor in 1 minute. The work per minute in foot-pounds $= \frac{2\pi nT}{12}$. As 1 horsepower equals 33,000 foot-pounds per minute, $\frac{2\pi nT}{12}$ foot-pounds per minute

$$= \frac{2\pi nT}{12 \times 33{,}000} \text{ horsepower}$$

$$= \frac{2\pi nT}{12 \times 33{,}000} \times 746 \text{ watts.}$$

Neglecting the losses due to friction, windage, etc., the power developed at the pulley must equal the electrical power converted in the armature. We thus have

$$\frac{2\pi \times 746 \times nT}{12 \times 33{,}000} = kI_a\Phi n.$$

Whence
$$T = \frac{12 \times 33{,}000\, kI_a\Phi}{2\pi \times 746}$$
$$= 84.5kI_a\Phi \text{ pound-inches.}$$

For any given motor k is a constant, and hence the torque is proportional to the product of the flux per pole by the armature current. At constant field excitation the torque of all direct-current motors is a maximum when the current is a maximum, which is on starting.

78. Theoretical Efficiency.—By efficiency of any piece of mechanism is usually meant the ratio of the useful work, or output of the machine, to the energy supplied, or input, to the machine.

The following discussion concerning the theoretical efficiency of the electric motor does not take into consideration hysteresis, eddy currents, friction, windage or the I^2R losses in field winding. The formula deduced is, therefore, only approximate; nevertheless, it is of importance and interest from a theoretical standpoint.

Let E = applied electromotive force,
E' = counter electromotive force,
R_a = armature resistance,
I_a = armature current.

Then I_aE = energy supplied to motor per second,
$I_a^2R_a$ = energy lost as heat per second in armature,

but
$$I_a = \frac{E - E'}{R_a}$$

and $EI_a - I_a^2R_a$ = energy converted into useful work.

Efficiency is then

$$\frac{EI_a - I_a^2R_a}{I_aE} = \frac{E - I_aR_a}{E}.$$

Substituting the value of I_a from above we get

$$\text{efficiency} = \frac{E - \dfrac{E - E'}{R_a}R_a}{E},$$
$$= \frac{E'}{E}.$$

This means that the approximate efficiency of a motor is the ratio of the counter electromotive force to the applied electromotive force. The nearer $E' = E$ the greater the efficiency of the motor. The commercial efficiencies of motors range from 60 to 95 per cent., depending upon the size of the machine and the kind of service.

Recapitulation

1. *An electrical generator* is a machine for converting mechanical energy into electrical energy.

2. *A continuous- or direct-current generator* is a machine which produces at the terminals of the armature a unidirectional pressure, that is, a pressure in one direction only.

3. *The essential elements of a generator* are a magnetic field, conductors, or armature which can rotate with reference to the field and a device for connecting the moving conductors to the external circuit.

4. *The armature in direct-current machines* is the symmetrically arranged group of rotatable inductors.

5. *The electromotive force induced in a group of conductors* rotating in a magnetic field is alternating. That is, the electromotive force in each conductor reverses periodically.

6. *The electromotive force induced in a single-loop armature* rotating in a uniform magnetic field is given by the expression

$$e = E_m \sin \omega t.$$

The average value is given by

$$E = \frac{4n\Phi}{60 \times 10^8} \text{ volts}$$

where Φ is the magnetic flux between the poles, and n is the number of rotations made by the armature in 1 minute.

7. *The commutator* of a direct-current generator is a rectifying device which changes the connections of the armature inductors with the external circuit every time the electromotive force in the inductor is reversed.

8. *The electromotive force of a multipolar generator* is given by

$$E = \frac{pn\Phi Z}{q60 \times 10^8} \text{ volts}$$

where p is the number of field poles, q is the number of parallel circuits through the armature, Φ is the flux per pole, Z is the number of inductors connected in series, and n has the same significance as in (6) above.

9. *A counter or back electromotive force* is generated in the armature coils of a motor as they cut across the magnetic flux. If E is the applied electromotive force, E' the counter electromotive force, and R the resistance of the motor armature circuit, which includes brushes, brush contacts, etc., the motor current is given by

$$I_a = \frac{E - E'}{R_a}.$$

10. *The torque of a direct-current motor* is given by

$$T = 84.5kI_a\Phi \text{ pound-inches}$$

where
$$k = \frac{pZ}{q60 \times 10^8},$$
$$I_a = \text{armature current}$$
and
$$\Phi = \text{flux per pole.}$$

11. *The efficiency of a direct-current motor* cannot be greater than the ratio of the counter electromotive force to the applied electromotive force. The maximum theoretical efficiency is given by

$$\text{theoretical efficiency} = \frac{E'}{E}.$$

CHAPTER VII

THE MAGNETIC CIRCUIT OF THE DIRECT-CURRENT DYNAMO

79. The Magnetic Circuit.—In the discussion of the magnetic field, it was shown that the magnetic lines are closed curves, Fig. 6. Under electromagnetic induction it was shown that the necessary condition for the development of an electromotive force is relative motion between a magnetic field and an electric conductor. The fundamental problem in the design and construc-

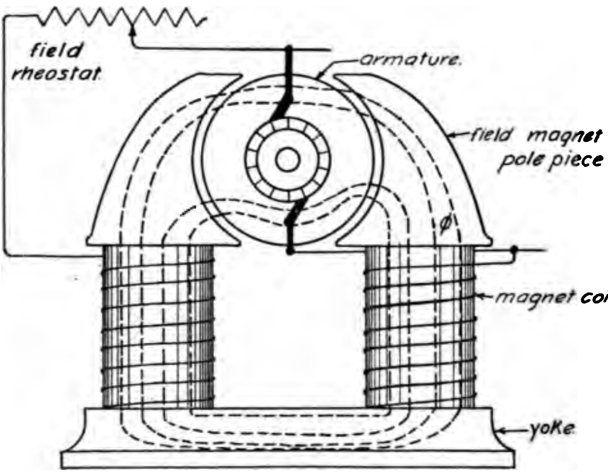


FIG. 57.

tion of a dynamo is, therefore, the production of a relatively strong magnetic field in which the armature conductors are to rotate. The simplest magnetic circuit of a dynamo is that of a two-pole machine shown in the diagram, Fig. 57. In this diagram the path of the magnetic flux Φ is represented by the broken lines. The magnetic circuit consists of the yoke, pole pieces, two air gaps, and armature core. The magnetism is produced by an electric current flowing in the magnet coils. The process of pro-

ducing the magnetic flux is called *excitation.* The different methods of excitation employed will be explained later.

The magnetomotive force produced in the field coils by the exciting current must be high enough to develop the proper magnetic flux around this magnetic circuit, and in order to secure this flux with as small an expenditure of energy as possible, all of the parts of the circuit must be carefully considered.

When the first direct-current machines were made, the laws of the magnetic circuit were not well understood, and accordingly the designs of the field magnets were often crude and clumsy.

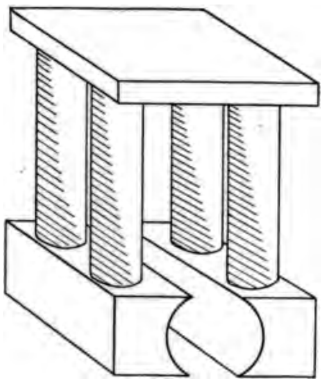


FIG. 58.

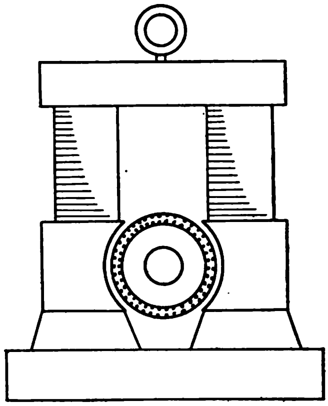


FIG. 59.

At first the field magnets were of the two-pole type, Fig. 57, and consequently the magnetic circuit was unnecessarily long and inefficient, or it was divided under the mistaken notion that such a construction would increase the effectiveness of the windings. Two forms of these early field magnets are shown in Figs. 58 and 59.

The design shown in Fig. 59, was inefficient not only on account of its excessive length, but also because the construction required the pole pieces to be separated from the bed plate, which was of iron, by a thick layer of non-magnetic material to prevent the shunting of the magnetic flux.

A more thorough and scientific knowledge of the laws and principles of the magnetic circuit soon caused modifications in the design of the dynamo magnets to conform to sound theory. From the principles already explained some of the necessary

changes in design may easily be inferred. Thus the equation for flux is:

$$\Phi = \frac{\text{magnetomotive force}}{\text{reluctance}}$$
$$= \frac{\mathcal{F}}{\mathcal{R}}.$$

The equation for magnetomotive force is

$$\mathcal{F} = 1.257 \text{ times ampere-turns}$$
$$= 1.257NI,$$

and the reluctance of a series magnetic circuit, different parts of which have different reluctances, is

$$\mathcal{R} = \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_3}{\mu_3 A_3} + \text{etc.}$$

The expression for flux, Φ, shows that for a given number of ampere-turns the flux varies inversely as the reluctance, $\mathcal{R}$. Hence, $\mathcal{R}$ must be small for a large Φ, and a small magnetizing force. But the equation for $\mathcal{R}$ shows that if the reluctance is to be small, the length of the magnetic path, l, must be short and the permeability, μ, must be high. The cross-sectional area, A, of the circuit depends upon the amount of the flux desired and it is so designed that the magnetic material will not become too highly saturated. The flux density in the air gaps of direct-current machines ranges from 45,000 to 60,000 lines per square inch. The permeability of iron varies between very wide limits depending on the grade of the material, and a good grade of soft cast iron or steel is generally used for the magnet cores, yokes, and pole pieces. The pole pieces are now commonly made of laminated iron riveted together and either bolted to, or cast into the yoke or frame as it is sometimes called. They are as short as they can be made, and still have sufficient surface for the field coil windings and other mechanical details which must be considered. The armature core is likewise built up of soft sheet-steel laminations of high permeability. The permeability of good sheet steel may be 5,000 and even higher. In comparison, the permeability of the air gap, which is unity, is very low. The air gap is, therefore, made as short as is consistent with good mechanical clearance between the armature and the pole pieces, and good commutation, which will be taken up later.

80. Multipolar Dynamos.—No matter how much the yoke and magnet cores are shortened in the design shown in Fig. 57, at best the magnetic path is relatively long. Two-pole generators of this form are, therefore, no longer made. The modern two-pole generator has a circular frame or yoke with two radially projecting pole pieces as shown in Fig. 60. Even with this modification the magnetic circuit is comparatively long. This, coupled with the fact that the armature speed of a bipolar machine would have to be very high for machines of large output, shows that the bipolar design is not suitable for large direct-current dynamos; accordingly, they are seldom made for outputs greater than 10 kilowatts. A diagram of the field and armature core of a four-pole machine is shown in Fig. 61. The path of the magnetic flux is indicated by the broken lines. It is quite evident that with the same depth of air gap and cross-sectional area of the pole pieces the reluctance of the mag-

Fig. 60.

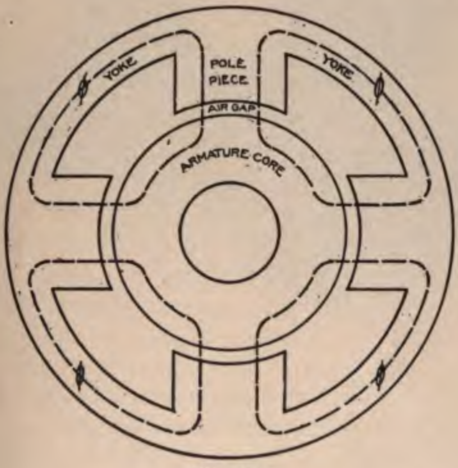


Fig. 61.

netic circuit of the multipolar machine is less than that of the bipolar dynamo. This type is more advantageous on account of the better proportions, more economical arrangement of materials, and, therefore, smaller weight, greater efficiency, larger

radiating surface, smaller floor space required, more satisfactory operation, and lower speed possibilities. Fig. 62 shows the frame, pole pieces, and field windings assembled of a multipolar generator. The pole pieces are made of laminated steel riveted together and bolted to the magnet yoke. A separate pole piece and coils are shown in Fig. 63. Some manufacturers prefer to cast weld the pole pieces into the magnet yoke.

FIG. 62.

The smaller machines have the magnet yoke and base cast in one piece. To permit the removal of the armature, and to give access to the field coils, the bearing pedestal on the commutator side is divided, the upper part being bolted to the base. By removing this pedestal, the armature can be pulled out endwise. On larger machines the field frames are divided either along a horizontal or vertical diameter, and bolted together. The plan of separation is shown in Fig. 62.

81. Interpoles.—When direct-current machines are subject to changes in the load the changes produce effects known as armature reactions. These armature reactions cause a shifting in space, as well as a weakening of the main magnetic field which in turn results in commutation troubles. To overcome these difficulties in commutation, small pole pieces are placed between the main

FIG. 63.

field poles. The windings on these interpoles, as they are called, are so designed and excited that the magnetic field due to them compensates for the shifting and other changes in the main magnetic field. The theory of operation of the interpoles will be explained more fully under commutation. Fig. 64 shows the relative position and size of the interpole pieces in comparison with main field pole pieces.

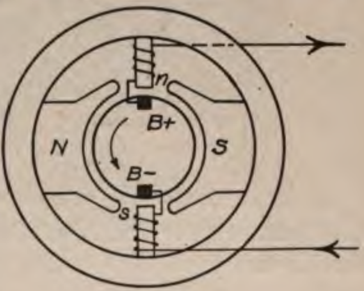


FIG. 64.

A rather original form of field construction is that used by the Ridgway Dynamo and Engine Co., which is shown in Fig. 65. The field ring proper is constructed of laminated steel, the punchings being securely clamped between flanged cast-iron rings. The pole pieces are also of laminated steel and consist of two parts, one the core for the main field coil windings, and the other termed the pole shoe, or pole face. The two parts are firmly bolted to the field ring by heavy cap bolts which pass through the field core and screw into the pole face. The pole faces are slotted in a direction parallel to the armature. Within these

slots is placed a winding known as compensating or balancing coils. The purpose of these coils will also be explained later.

Between the pole faces are placed the commutating or interpoles. As is evident from Fig. 65, the interpoles are also of laminated steel. The interpoles are supported by brass keys driven into slots in the sides of the interpoles and the adjacent pole faces. A complete field winding and frame is shown in Fig. 66.

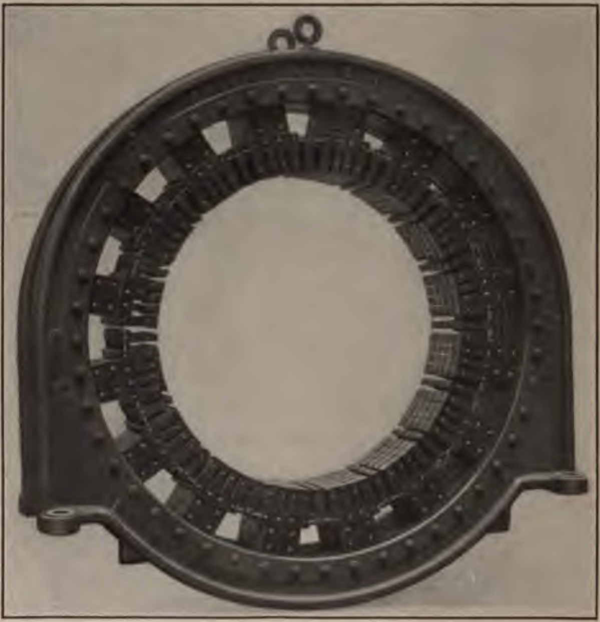


FIG. 65.

82. Magnet-field Frames of Turbo-generators.—The magnet-field frames and cores illustrated and explained in the preceding section are for comparatively low-speed, belted or direct-connected generators and motors. The principles governing the construction of the magnetic-field frame of the high-speed turbine-driven direct-current generator are the same as for the other machines. The details of construction are, however, somewhat different. In the first place as the armature runs at a high speed it must be of comparatively small diameter, and accordingly the magnet frame is smaller in diameter than that of a generator of slower speed and of the same kilowatt rating. The increase in the speed of the armature makes possible a greater output per

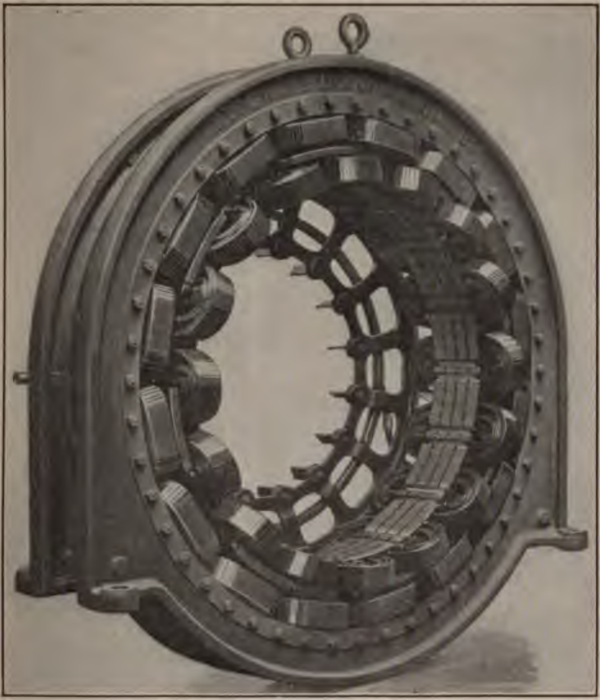


FIG. 66.

FIG. 67.

pound of material. The losses per pound of material are also increased and accordingly proper ventilation must be given careful consideration. Fig. 69 shows the construction of the Ridgway direct-current turbo-generator interpole magnet-field frame.

83. Magnetic-field Calculations.—As this text is not intended for the designer, what follows is intended merely to illustrate the

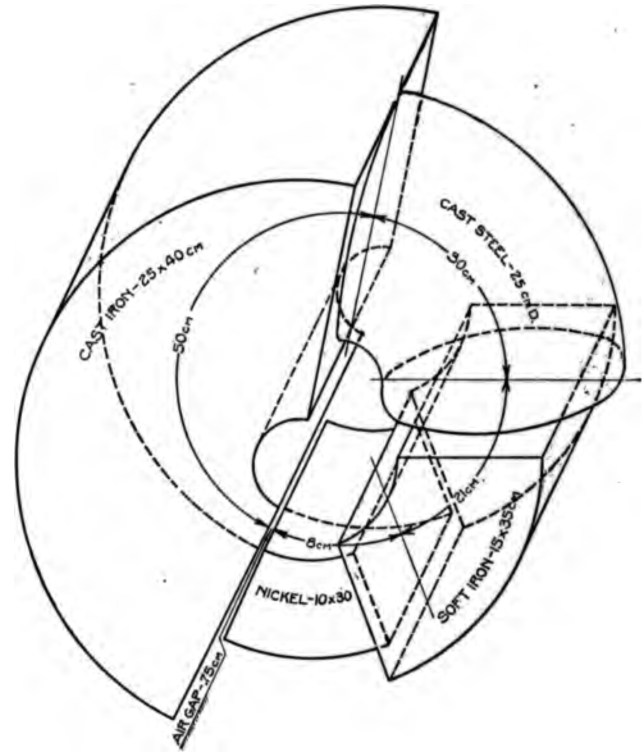


FIG. 68.

effects of materials of different permeabilities and dimensions in the magnetic circuit.

Example

Assume a problem as represented by Fig. 68, when the magnetic circuit is composed of different materials of different cross-sections, lengths, and permeabilities, we have given the following data:

	Parts				
	A	B	C	D	E
h in centimeters, l	8	21	30	50	0.75
eability, μ	63	1,760	925	157	1
in square centimeters, A	300	525	490.87	1,000	720

be required to calculate the flux density and magnetomotive force sary to develop this flux density in each section for a total flux of ,000 lines.

definition the flux density is the total flux divided by the cross-sec- area, or $\mathcal{B} = \frac{\Phi}{A}$; and $\mathfrak{F}$, the magnetomotive force, is equal to $\frac{\mathcal{B}l}{\mu}$. ; these relations we find the following values:

	Parts				
	A	B	C	D	E
$\mathcal{B} = \frac{\Phi}{A}$	20,000	11,428	12,223	6,000	8,333
$\mathfrak{F} = \frac{\mathcal{B}l}{\mu}$	2,540	136.3	397	1,910.8	6,250

magnetomotive force for the whole circuit is the sum of the magneto- e forces for the several parts = 11,234.1 gilberts.

. **Useful and Leakage Flux.**—The useful flux of a dynamo at which passes through the armature and is cut by the ture conductors as they revolve. When the field cores are ly saturated, all of the flux does not pass from the pole face the armature, but some of it follows paths of lower reluc- e. The flux that is not useful in generating an electromotive is known as leakage flux. In a well-designed dynamo this ge flux is reduced to a minimum by designing the magnetic it so that the lowest reluctance is through the armature.

. **Field Windings.**—The magnetic field of dynamos is pro- d by electric currents flowing through properly designed coils d around the pole pieces. In the early days of dynamo truction the field cores were round and the field coils were

wound on metal shells which were then slipped over the field cores. An excessive amount of insulation was used which prevented the free radiation of heat engendered in the winding by the current.

"As heat-conducting and radiating conditions and ventilation became better understood, the outer insulation on the coils was reduced materially, and precautions were taken to ventilate the field windings more thoroughly. Series windings were better exposed to the air, and shunt windings were, in some cases, subdivided in order to increase the effective ventilating surfaces. Also, in view of the fact that, with heavy, deep coils, the center portion would be roasted out, while the outside part would be comparatively cool, practice gradually tended toward comparatively shallow coils, arranged for good air circulation over them. In series coils and in commutating-pole windings, where comparatively heavy strap or bar conductors are used, the individual turns are now separated by air spaces in many cases. In other words, in modern design, low temperatures are obtained not by piling on material, but by improvements in heat dissipation."[1]

FIG. 69.

With respect to the manner in which the field coils are connected, we have the shunt and series coils. The magnetomotive force of the current in the shunt coils produces the main flux of the dynamo. As a rule the shunt coils carry a relatively small current and so are wound with comparatively small round or square wire and contain a relatively large number of turns. By such a construction the losses in the field windings are reduced to a minimum. The coils are usually wound on wooden forms

[1] B. G. LAMME, *Electric Journal*, vol. 11.

or moulds; they are rectangular in shape with rounded corners, and with the layers having approximately the same number of turns. Due to limitations of space the coils may be tapered or wedge-shaped by placing fewer turns in successive layers. Such a coil is shown in Fig. 69. In other cases the coil may be quite flat as in railway motors.

A moisture-proof insulating compound is forced, under pressure and at a high temperature, into all parts of the coils. The melting point of this compound is higher than the highest temperature

Fig. 70.

the coils are liable to experience in operation. The heat conductivity of the insulating compound is also relatively high and thus it is quite effective in maintaining a low operating temperature.

For railway series motors and for large direct-current generators there has been developed a strap or ribbon winding. The flat strip or ribbon of copper is wound edgewise with strips of paper or asbestos between the layers. This makes a very compact and solid coil and as the bare copper of such coils is exposed to the air the heat-radiating properties are superior to those of the other form.

An interesting method of ventilation is employed by the General Electric Company on its commutating pole type generators.

The series and shunt coils are wound side by side, ample ventilation being provided lengthwise through each coil and between the coils. Fig. 70 shows this type of coil. When the coils are in place on the field cores, they are connected so that adjacent poles are of opposite polarity.

Recapitulation

1. The magnetic circuit of the dynamo consists of the iron yoke, pole pieces, armature core, and air gaps.

2. The magnetic circuit is made as short as possible. The process of producing the magnetic flux is called excitation.

3. Two pole direct-current generators are seldom built in sizes larger than 10 kilowatts.

4. Multipolar dynamos are more efficient than bipolar machines on account of the more effective arrangement of the material and shorter magnetic circuit.

5. Interpoles or commutating poles are small pole pieces placed between the main field poles. They are excited by a series winding. Their function is primarily to aid in commutation.

6. By useful flux of a dynamo is meant that flux which passes through the armature and is cut by the inductors. By leakage flux is meant that flux which is not cut by the inductors.

7. The essential properties of field windings are compactness, the ability to withstand comparatively high temperatures, and effective heat radiation. The coils are usually form-wound, and may be either of wire or flat strips.

CHAPTER VIII

ARMATURES

86. Introductory.—The elementary and fundamental principles of electromagnetic induction have been explained in Chapters III and VI. The application of these principles to practical machines will now be taken up.

87. Armature.—In direct-current machines the magnetic field is stationary while the conductors rotate. In these machines the rotating element is the armature no matter whether the dynamo is a motor or a generator. The armature of a direct-current dynamo may thus be defined as the rotating member in the coils of which the electromotive force is induced. In the case of a

FIG. 71.

generator the current flows under the influence or in the direction of this induced electromotive force, while in the case of a motor the current flows against the induced pressure, the actuating pressure in this case being from some outside source.

88. The Armature Core.—The armature consists of a core, windings, and commutator. The core is built up of laminated iron which may be keyed directly to the shaft, as is the practice in small machines, or to a spider as shown in Fig. 71. The armature core is built up of steel stampings of high magnetic permeability. For large machines the stampings are in the form of segments of a circle. These are then assembled on the arms of the spider. For machines of comparatively small size

the laminations are punched in a complete ring and are assembled on the shaft or spider to which they are securely keyed to prevent any turning movement. The assembled core is also securely clamped between a core head which is a part of the spider and an annular casting at the other end. The core head also furnishes support for the coils.

The cores of the earlier armatures were smooth, and the coils were held in place by friction only. Any sudden change in speed, or a short-circuit of the armature winding quite often resulted in shifting the coils. To remedy this difficulty the slotted armature core was developed. In one of the first experiments with slotted armature cores, the winding was pushed through holes near the periphery. When the machine was put in operation it was soon discovered that excessive sparking was present at all times even with only the exciting current flowing through the coils. Cutting the holes open so as to form slots remedied this difficulty. Forms of slots and teeth are shown in Fig. 72.

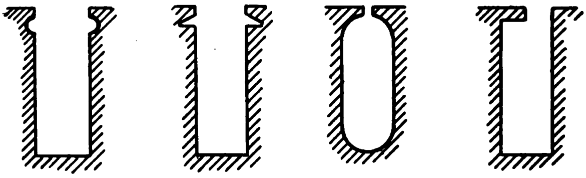


Fig. 72.

Several factors govern the design of the armature teeth and slots. Among the most obvious may be mentioned facility in winding, and commutation. The open slot with parallel sides is commonly used on large armatures, for the reason that formed coils can easily be slipped into place. These coils are then prevented from flying out by bands of wire, or by wood or fiber wedges driven in grooves at the tips of the teeth. The best proportions of teeth, slot, and air gap were mainly determined by experiment.

89. Energy Losses in Armature Core.—The function of the armature core is to provide a path of low reluctance for the magnetic flux, and to furnish a rigid support for the armature coils and a means for revolving them. When the armature rotates the magnetic lines shift around the core. This shifting of magnetic lines has the same electrical effect upon the iron of the armature core as upon the inductors wound on its surface. That is, an electromotive force is induced in the core. If we apply Flem-

ing's right-hand rule it becomes evident that this electromotive force is induced in such a direction that if the core were solid, currents would flow parallel to the shaft. The intensity of these currents would be determined in accordance with Ohm's law. These currents, known as *eddy currents*, if permitted to flow, would unnecessarily heat the armature causing deterioration of the insulation and a waste of energy. To reduce this loss of energy and heating to a minimum the eddy currents are made as small as practicable by making the resistance of their path very high. This is done by making the core of thin laminations insulated from each other by a coat of insulating varnish or merely by the layer of oxide that forms on the laminations. As is evident from Fig. 71, the planes of the laminations are at right angles to the shaft. In commercial machines the laminations are usually about 0.02 to 0.035 inch thick.

The armature core is the seat of another energy loss which can be reduced to a minimum only by the use of steel of very high permeability. Every time any part of the core passes from beneath a magnetic pole of one polarity under a pole of the opposite polarity the magnetic character of that part of the core is reversed. This continual reversal of the magnetism of the core results in what is known as hysteresis loss. This energy loss manifests itself as heat in the armature and is wasted.

90. Ventilation of Armature.—Together with the two sources of heat mentioned the current in the inductors also develops heat. To prevent an excessive increase in the temperature of the armature, radial ventilating ducts are provided in the core. These ducts are formed by spacing pieces placed at proper intervals. One form consists of U-shaped steel stamping riveted to one of the laminations. Other manufacturers use brass strips riveted to a punching of steel. The fanning action of the armature, when rotating, forces air through the spider and through the ventilating ducts in the core. After leaving the armature the air passes through the ventilating ducts of the field core, when it is constructed with ducts, and in other cases merely causing a current of air to flow around the pole pieces thus cooling all the active parts.

91. The Commutator.—The function of the commutator is to change the connections of the armature coils with the external circuit every time the current in the coils is reversed. The commutator thus performs a most important function and as a con-

sequence it is the source and seat of the most prominent direct-current dynamo troubles.

At present the only material used for commutator bars is hard-drawn or rolled copper. Many experiments have been made with other materials, but on account of its high heat and electrical conductivities copper has proved the most satisfactory.

The copper bars are at first sawed slightly larger than the desired size when finished. In medium sizes, before the commutator is built up, a copper bar, called the neck, is brazed to each segment, Fig. 73. This neck serves to make connection

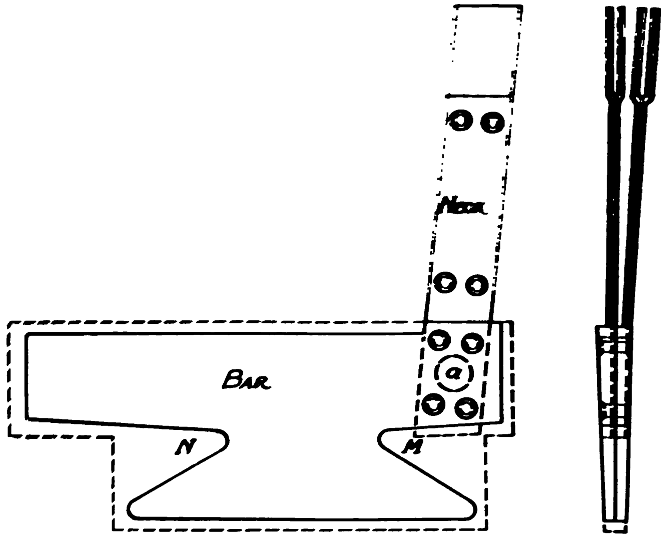


FIG. 73.

with the armature winding. In the smallest sizes and in most motor commutators, the neck and bar are in one piece and the insulation is fitted between the necks as well as the segments.

As is shown by the end view, Fig. 73, the bars are tapered so that when assembled they will form a ring. Molded mica about $\frac{1}{32}$ inch thick is placed between the bars and the assembled commutator is firmly clamped within an iron ring. In this condition it is placed in an oven and subjected to a temperature of about 125° to 150°C. This baking process softens the bond and adjusts the strips of mica to the inequalities of the copper bars. If this were not done the mica strips would adjust themselves in service and a loose commutator would result. When the com-

mutator has been thoroughly baked it is allowed to cool after which both the inner and outer surfaces are machined off. A test is then made for short-circuits between bars. A commutator with machined ends is shown in Fig. 74. It will be noticed that a groove whose cross-section is a V has been turned in the end. A similar groove is cut in the other end also. A cast-iron bushing having a projection to fit one of these grooves is placed within the ring of copper bars, and a brass ring having a similar projection is placed in the V-shaped groove, on the other end, and

FIG. 74.

clamped to the bushing by bolts. The commutator bars are insulated from the bushing, and from the brass ring by moulded mica insulation. When the clamping bolts are properly tightened, the outer clamping ring may be removed and the outer surface machined off. A large commutator ready for mounting is shown in Fig. 75.

There are several reasons for the use of mica between the commutator bars. One is its elasticity, which keeps the spaces filled solidly, regardless of the expansion and contraction of the commutator; another is its ability to withstand relatively high temperatures without deterioration; and still another is the fact that it wears down at about the same rate as copper. The importance of this last property has been considerably reduced within

recent years by the practice of undercutting the mica, that is, cutting it below the level of the copper.

The insulating properties of mica are, of course, essential, but as the maximum voltage between commutator bars is seldom above 25 volts, substitutes with satisfactory electrical properties could easily be found. Up to the present time, however, no substitute has been found which possesses the requisite mechanical properties.

92. Armature Windings.—The wire wound on the armature core and in which the electromotive force is induced as the armature rotates is called the armature winding. Armature windings may be classified with reference to the position they occupy

FIG. 75.

on the armature core, or with reference to the manner of their distribution on the core and their connections to the commutator bars. If the first method of classification be employed we have:

1. Ring-armature winding.
2. Disk-armature winding.
3. Drum-armature winding.

The first two types are not in commercial use, and hence merely an explanation of their meaning will be sufficient.

93. Ring-armature Winding.—The ring armature as ordinarily used consists of a continuous spiral of wire wound around the ring core with taps taken off to connect to the commutator segments, as shown in Fig. 76. In this way there is obtained a winding with a large number of conductors in series capable of generating a large electromotive force. Since certain inductors are at their position of zero pressure, while others are at inter-

mediate values up to the maximum value, their superimposed or added pressures give a practically uniform pressure. It will be noticed that the winding has two paths for the current from brush to brush. That is, the two paths of the armature winding are in parallel. The path of the magnetic lines through the armature

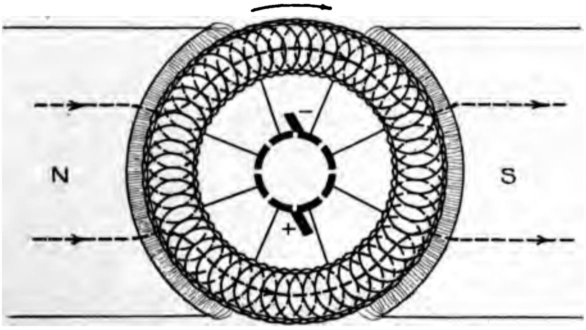


FIG. 76.

core is indicated by the dotted lines of Fig. 76. The magnetic lines follow the ring and are not cut by the conductors on the inside of the ring. For this reason less than half of the wire on the ring armature is active in generating an electromotive force.

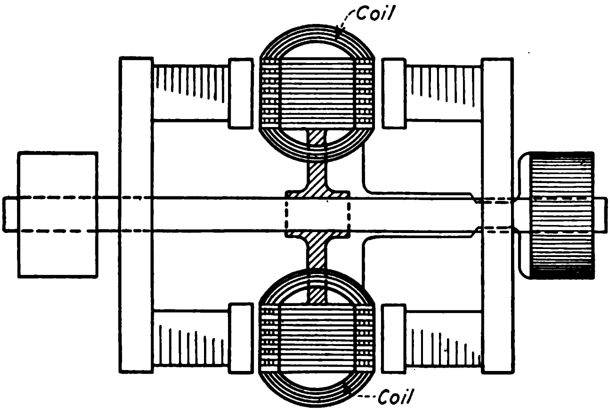


FIG. 77.

94. Disk-armature Winding.—There is very little difference between the disk and ring armatures in so far as construction is concerned. As shown by Fig. 77, the core of the disk armature is, in form, a flat ring. The winding consists of several coils

wound around the core and uniformly spaced around its periphery. The real difference between the ring- and disk-armature dynamos is the relative position of the magnet poles. In the dynamo with a ring armature the magnet poles project radially toward the ring, while in the dynamo with a disk armature the pole pieces extend parallel to the axis of the armature. Both ring and disk armatures are now obsolete.

95. The Drum-armature Winding.—The drum winding has its coils properly spaced around a core of magnetic material in such a way that all conductors parallel to the shaft are on the surface of the core and are active in inducing pressure. The conductors passing across the front or back of the core to connect the active conductors cut no magnetic flux and no pressure is induced in that part of the winding. In most windings these

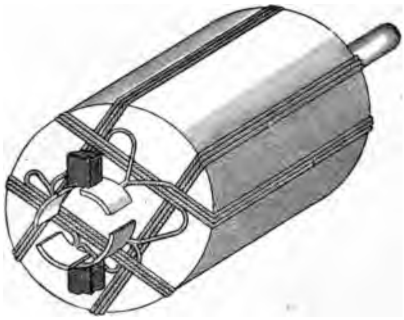


FIG. 78.

connections are comparatively short and a greater per cent. of the winding is active than in the ring winding. Fig. 78 represents a simple four-coil drum winding connected to a four-part commutator. This is merely an illustration of a drum winding and is not intended to show actual construction. As shown in Fig. 71 the armature core is almost invariably slotted, and the slots are uniformly spaced around the core. The winding is therefore also uniformly spaced around the core and not as shown in Fig. 78.

96. Electrical Characteristics of a Drum Winding.—In Chapter VI it was shown that when a simple loop of wire is rotated between two magnet poles the induced pressure fluctuates as a sine curve or nearly so. If two loops whose planes are at right angles to each other are connected to a four-part commutator

and rotated between the poles of a magnet the induced electromotive force will be the sum of two sine curves, and as the commutator interchanges the connection every half cycle, the external electromotive force wave will have a form shown in Fig. 79. The resultant voltage curve is smoother than when only one loop is used. Increasing the number of inductors on the surface of the armature has the effect of making the pressure more uniform.

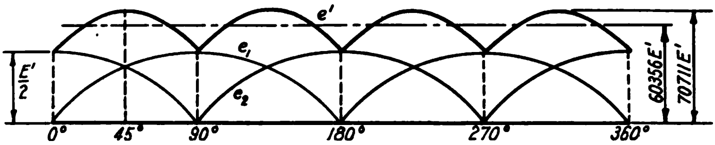


Fig. 79.

97. Lap Winding.—If the arrangement of the wire on the surface of the armature core is the basis of a classification we have two types, *lap* and *wave* winding. A simple lap winding for a two-pole dynamo is shown in Figs. 80 and 81. This represents an end view of an armature. The ends of the inductors are represented by small circles numbered 1 to 26. The divided ring in the center of the figure represents the commutator, consisting

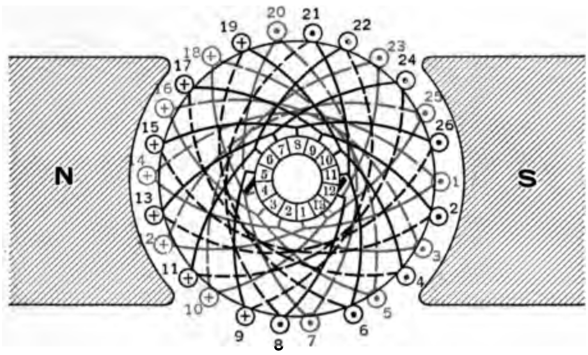


Fig. 80.

of 13 segments. The solid and broken curved lines represent the front and back connections, respectively, of the armature winding.

If the direction of motion is counter clockwise then the electromotive force in the inductors under the N-pole is from the commutator end towards the back, or from above into the paper.

These inductors are indicated thus ⊕. The electromotive force in the inductors under the *S*-pole is directed, from the back toward the commutator end, or out of the plane of the paper. These inductors are represented thus ⊙.

Two inductors with their end connections, such as 1 and 12, 3 and 14, etc., form a coil. Each coil may consist of several inductors, or of only two as shown. Usually there will be several, the number being determined by the voltage, and capacity of the machine. If the conditions are as indicated in the diagram, the left brush is negative, that is the current returns to the armature by

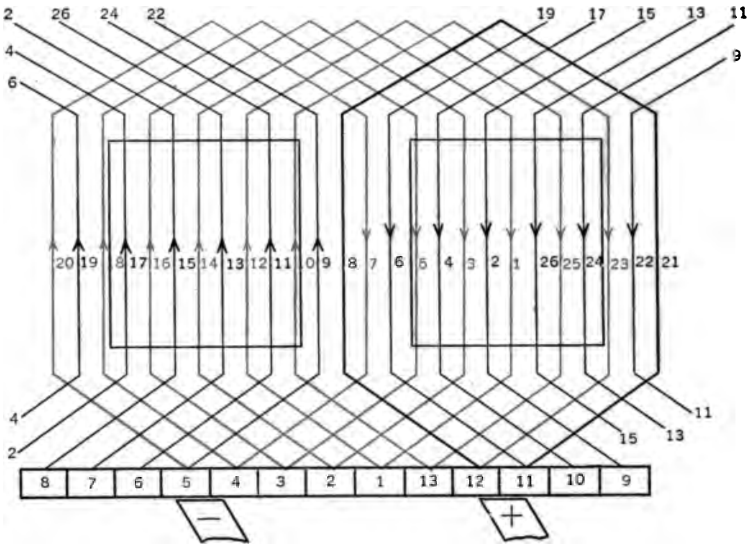


FIG. 81.

this brush. If we trace the path of the current flow from this brush we find that it flows through two circuits in parallel. As the current leaves commutator segment 5 it divides, one half of the current going to inductor 20 and the other to inductor 9. Tracing the current flow from inductor 9 we see that it flows across the rear end of the armature to inductor 22, then from inductor 22 across the front of the armature to inductor 11; from 11 to 24, then to 13, 26, 15, 2, 17, 4, 19 and 6 in succession, to commutator segment 11 and thence to the brush at the right which is the positive brush of the dynamo. Thus, one half of the current flows through inductors 2, 4, 6, 9, 11, 13, 15, 17, 19, 22, 24, 26, and the end connections. Likewise, if we trace the current flow through

the other circuit we see that this circuit consists of inductors 10, 12, 14, 16, 18, 20, 23, 25, 1, 3, 5, 7, and end connections. These two circuits are indicated in the figure in black and red respectively.

The foregoing explanation holds for a two-pole machine. A similar winding for a four-pole machine is shown in Fig. 82. The line current divides and enters by the two negative brushes. If we trace the path of the part that enters at commutator segment 1 we find that it divides, one part going by way of inductors 4, 17, 2, 15 and out by way of commutator segment 8. The

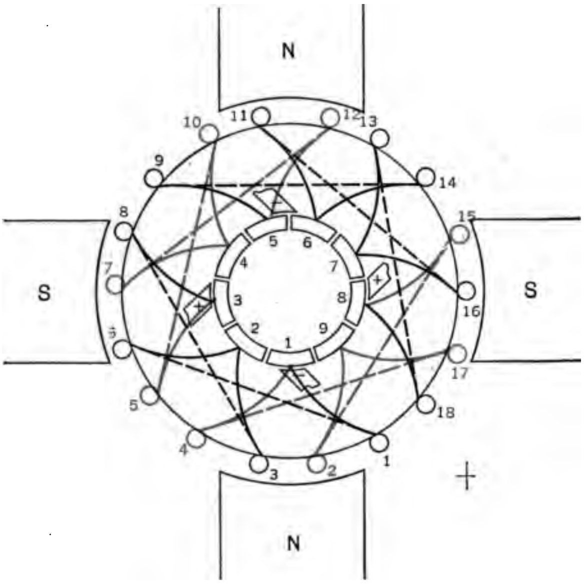


FIG. 82.

other part goes by way of inductors 1, 6, 3, 8 and commutator segment 3. The current that enters by way of the upper negative brush divides in the same manner. It is thus evident that for this type of winding there are as many paths through the armature as the magnetic field has poles.

If the windings shown in Figs. 80 and 82 be cut and unrolled flat, the arrangement and connections of the inductors, and current paths, may be illustrated by the diagrams 81 and 83. An examination of these diagrams shows that the winding laps back over itself and for this reason it is called *lap* winding. It is also

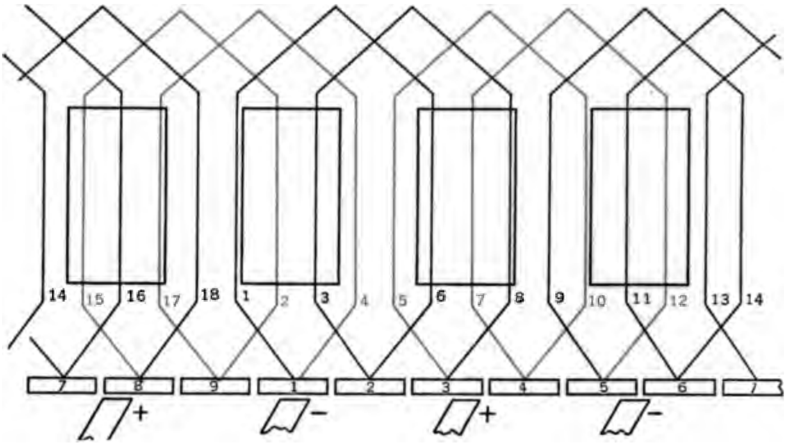


FIG. 83.

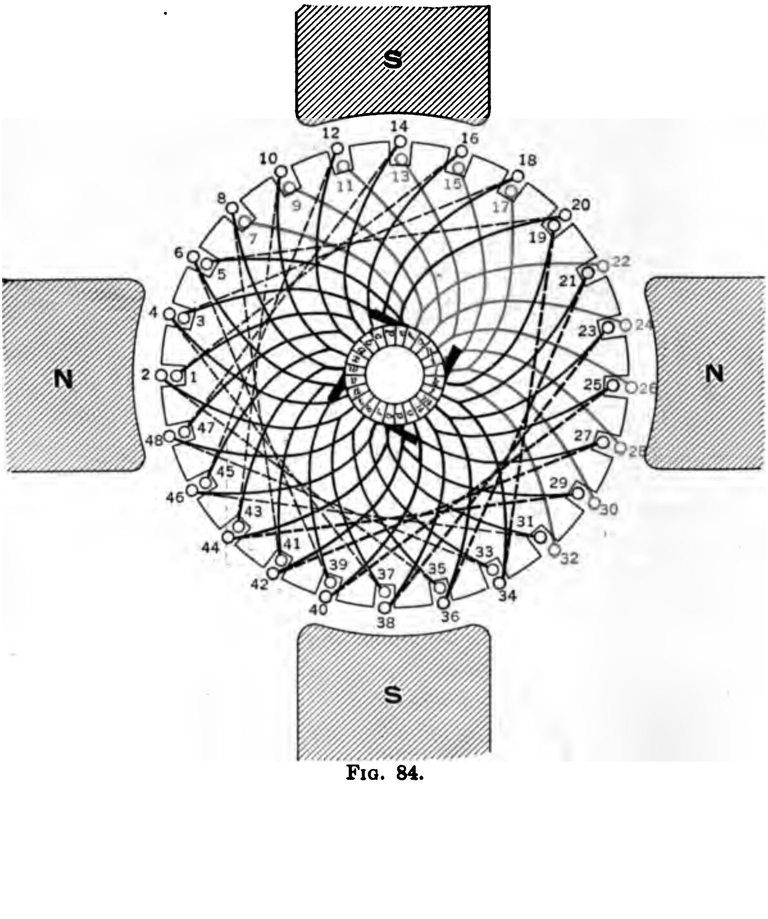


FIG. 84.

called *parallel* winding because there are as many current paths in parallel as there are field poles. Another arrangement of this type of winding is illustrated by Fig. 84, where two conductors per slot are shown. A careful tracing of the current flow from brush in contact with commutator segment k, shows that one circuit consists of inductors 32, 17, 30, 15, 28, 13, 26, 11, 24, 9, 22 and 7. This circuit is shown in red. The other circuits can easily be traced.

98. Wave Winding.—Another and more common form of winding is shown in Figs. 85 and 86. In this winding the end of each coil is connected to the beginning of the one having a cor-

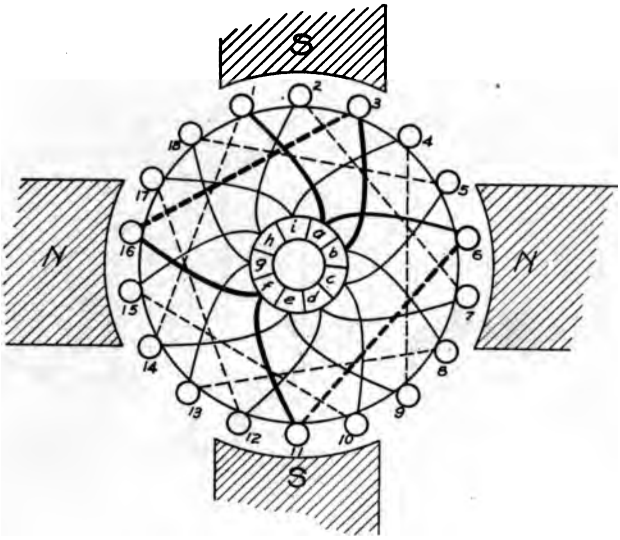


FIG. 85.

responding position under the next magnet pole; and the winding in consequence is wave-shaped when developed, Fig. 86. For this reason it is known as *wave* winding.

A careful tracing of the circuits in Fig. 85 shows that there are but two paths through the armature regardless of the number of poles and half the coils on the armature are connected in series in each path or circuit, whereas the lap winding has as many paths as there are poles, and a smaller number of coils in series. The wave winding is thus suitable for higher voltages than the lap winding. Of two four-pole machines having coils of the same number of turns and conductors of the same size, the armature with the wave winding will be capable of developing double the

voltage at half the current of that of the lap winding. The wave winding is cheaper and more easily installed on smaller machines where the number of turns is necessarily limited, and for these reasons it is almost universally used on the smaller direct-current dynamos of the multipolar type.

99. Closed- and Open-coil Windings.—An examination of the drum windings explained will show that the coils in every case form one continuous or closed winding. Connections to the commutator are made by suitable taps. Only closed windings are at present employed on direct-current dynamo armatures. Open coils are used only on alternators, hence will not be discussed here.

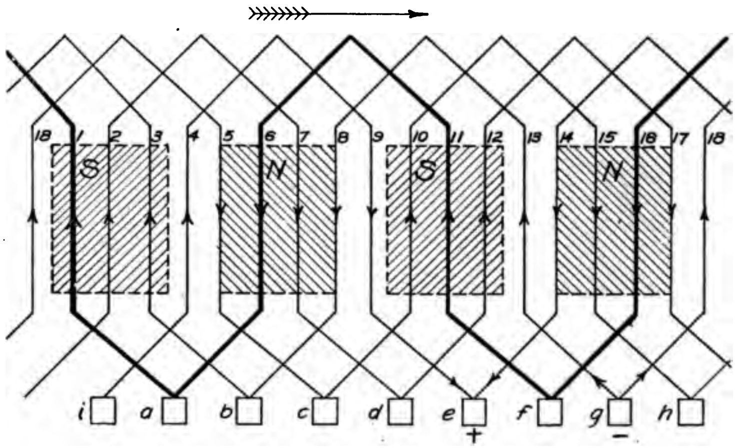


FIG. 86.

100. Number of Brushes Required.—Referring again to Fig. 82 we see that the current flows from commutator segments 1 and 5 to the armature and from the armature coils to segments 3 and 8. That is these commutator segments are junction points of the currents. It is thus evident that brushes must be placed at these points. For a lap winding there are required as many brushes as there are poles.

The condition is, however, different with reference to the wave winding. For instance, in Fig. 85 one brush may be in contact with commutator segment *e* and the other brush may be in contact with segment *g*. These two brushes are sufficient, for at no other point in the armature will the current flow in opposite directions. Another pair of brushes may be placed, one in con-

tact with commutator segment c and the other in contact with i, but these brushes are unnecessary.

101. Mechanical Construction of Armature Coils.—The armature coils are first wound on properly shaped forms or moulds.

FIG. 87.

After the coils are removed from the forms they are taped, dipped in insulating varnish and baked before being inserted in the armature slots. A pair of finished coils for lap winding is shown in Fig. 87, while those shown in Fig. 88 are for wave winding. The mode of installing these on the armature core is shown in Fig. 89.

FIG. 88.

In the earlier construction of direct-current generators and motors, the coils were held in place by bands of brass or steel wire, and the end windings were held in place by brass or bronze end bells. At present the use of end bells has been almost en-

tirely superseded by banding with steel wire which makes an open construction, thus giving good ventilation. Wire bands are, however, used very seldom for retaining the armature coils within the slots. For this purpose fiber or wooden wedges are employed. With the use of these, repairs can be made more easily, since the wedges need be removed only from the slots in which the defective coils lie. The use of steel bands is also objectionable because where they cross the slots they form closed magnetic circuits around the armature coils increasing the armature self-

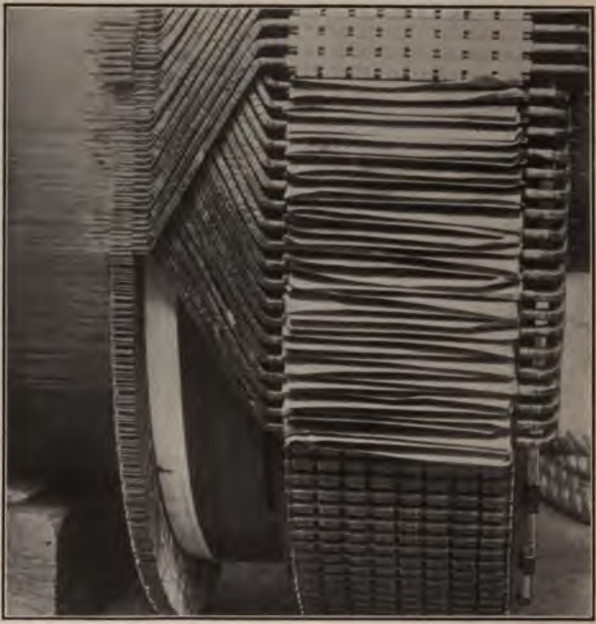


FIG. 89.

induction which in turn makes it more difficult to secure good commutation.

For machines which require a very rigid construction, such as railway motors, the banded armature has been found to best answer the purpose. For generators and most motors, other than railway motors, wedges are used almost exclusively. A completed armature is shown in Fig. 90.

102. Turbo-generator Armature.—The electrical and magnetic principles explained in the preceding articles also apply to the

armatures of turbo-generators, but owing to the high speed at which turbo-generator armatures are driven, they are smaller in diameter and a much more rigid construction is necessary, Fig.

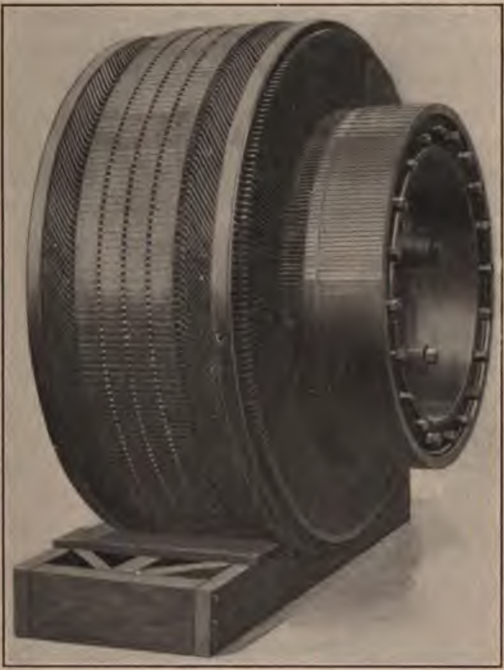


Fig. 90.

91. The armature core is built up of very thin steel punchings, solidly keyed to the spider which is merely an enlargement of the

Fig. 91.

shaft. The armature coils are held in place by wedges, and the end windings are held against centrifugal force by bronze end bells. The commutator bars are held in place by internal wedges

and external steel rings shrunk on over mica insulating bands. Fans for ventilation are provided at the commutator and the opposite end of the armature.

103. Influence of Type of Winding upon Electromotive Force of a Multipolar Dynamo.—In Chapters III and VI it has been shown that the electromotive force developed by a given dynamo depends upon the flux per pole, speed, and number of inductors in series between the brushes. The general principles apply to multipolar machines with lap- and wave-wound armatures, but slight modifications have to be made in order to take into account the number of parallel paths in the armature. Referring to Figs. 82 and 83, we learned that there are four paths for the current through the winding. The electromotive force between a positive and negative brush will be determined by the number of inductors in series between the brushes. The total number of inductors on the armature is 48; then as there are four paths, there will be $^{48}/_{4} = 12$ inductors in series between two poles. These inductors, in making n revolutions per minute, will cut the flux under four poles n times. If Φ is the flux per pole, the average electromotive force for the armature of Fig. 86 will be

$$E = \frac{4\Phi n \times 12}{10^8 \times 60} \text{ volts.}$$

In general, $$E = \frac{pn\Phi Z}{q \times 60 \times 10^8}; \text{ see Article 72.}$$

This expression shows that the wave winding for which $q = 2$ will develop a higher voltage than the lap winding for which $q = 4$, other things being equal.

Examples

1. A six-pole generator has a lap winding. If there are 300 inductors on the surface of the armature, and if the flux is 900,000 lines per pole, what will be the voltage between the brushes at a speed of 1,500 revolutions per minute?

Solution.—

$$E = \frac{pnZ\Phi}{q \times 60 \times 10^8}.$$

$$p = 6.$$
$$n = 1{,}500.$$
$$\Phi = 900{,}000 = 9 \times 10^5.$$
$$q = 6.$$
$$Z = 300.$$

Then $$E = \frac{6 \times 1{,}500 \times 9 \times 10^5 \times 300}{6 \times 60 \times 10^8}$$
$$= 67.5 \text{ volts.}$$

2. What voltage will the generator in question 1 develop if the winding be wave connected, other conditions remaining as before?

Solution.—All the conditions are the same as before, except q which is 2 instead of 6, hence
$$E = \frac{6 \times 1{,}500 \times 9 \times 10^5 \times 300}{2 \times 60 \times 10^8}$$
$$= 202.5 \text{ volts.}$$

104. Brushes and Brush Holders.—Although brushes and brush holders can not properly be considered a part of the armature, nevertheless as they are the connecting link between the commutator and external circuit, a brief treatment of them will be given here.

On some of the earliest machines, brushes made from steel bars were employed, but owing to the relatively high resistance and magnetic properties of steel these were soon replaced by copper. The high electrical conductivity and elasticity of copper, at first, appeared to be very desirable properties for brushes. In many instances, however, the high conductivity was not an advantage. The brush short-circuits two or more commutator segments; inevitably a current flows between the armature coils whose commutator segments are short-circuited. The high conductivity of copper brush permitted excessive short-circuit currents to flow. These excessive currents burned, not only the brushes, but the commutator segments as well. Another objectionable feature of copper brushes was the destructive cutting and abrasion of the commutator that sooner or later developed. This cutting was especially prominent where the brushes were made of solid bars of copper. To overcome this difficulty the brushes were made of several sheets or leaves of copper or brass gauze; but even this did not prove wholly satisfactory; nevertheless, for low-pressure and large current-output machines, thick copper brushes are still employed. On high-potential machines, especially on railway generators and motors, some form of carbon brushes is used.

The carbon employed is usually a mixture of powdered coke and graphite with a trace of paraffine for lubricating purposes. The exact proportions of the ingredients vary with different manufacturers. As generally made the powdered coke and graphite are thoroughly mixed in the desired proportions and then the mixture is compressed into large slabs of nearly the

desired thickness. These slabs are then baked and afterward milled to the required dimensions.[1] As it is very important that the carbons fit closely in the holders, each individual carbon block is tested for thickness and must be between 0.002 inch and 0.010 inch thinner than the opening of the holder into which it is to fit. No such close fit is required in the width of the carbon, a variation of $\frac{1}{32}$ inch being allowed in this dimension.

FIG. 92.

For machines of large current capacity several individual carbon blocks are assembled, side by side, into proper holders, thus constituting a set. The number of blocks necessary to form a set in any case is determined by the current output or intake of the machine, the brushes being designed to carry from 30 to 50 amperes per square inch of cross-sectional contact area.

The electrical connection between the brush and holder is usually made by a flexible conductor of braided copper. One end of this conductor is soldered or bolted to the carbon brush, which

[1] Dimensions for standard sizes are given by MARTINDALE in *Electrical Review and Western Electrician*, Vol. 10, p. 503.

in the first case must be copper-plated, and the other end is fastened to the brush holder, usually by a bolt. This construction is well shown in Figs. 92, 93, 94 and 95.

Close contact of the brush with the commutator is maintained by springs which may be either flat or spiral. These springs are

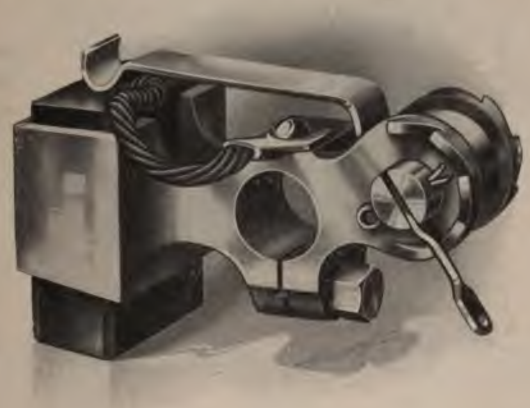


FIG. 93.

adjustable and are so designed as to give practically constant pressure throughout the useful life of the brush. This pressure should be from 1.5 to 2 pounds per square inch of contact area. Any greater pressure does not materially decrease the contact resistance, but increases the friction between the brushes and commutator, resulting in loss of energy and heating the commutator.

FIG. 94.

With the exception of railway motors, it is the usual practice to set carbon brushes at a slight angle to the face of the commutator. This position gives much smoother action and less chattering than the radial position. It makes little if any difference in which direction the armature rotates. Some claim that a better contact is maintained between the brush and brush box if the armature is turned in the direction of the inclination of the brush. As only a part of the current is conducted through the box, this is of no great importance.

On railway motors the brushes are usually set radially. A of railway motor brushes is shown in Fig. 96. The brush pres is adjustable by means of a pawl and ratchet device, each sp being adjustable separately.

Fig. 95.

The carbon brush holders may be divided into two gen classes, the sliding or box type and the clamped type.

Fig. 96.

In the sliding type the individual carbon is placed in a ret ing box which permits free movement of the carbons radi Figs. 94 and 96 illustrate this type of holder.

The clamped type is that in which the carbon is bolte

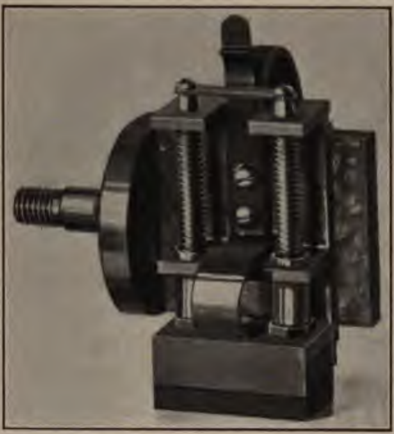


Fig. 97.

Fig. 98.

clamped rigidly to a pivoted support. In this type of holder the flexible shunt is in contact with the brush over its entire rear surface. A type of brush holder that is midway between these two general classes is that used by the Ridgway Dynamo and Engine Co., whose brush, brush holder, and stud are shown in Fig. 97. The brush is held at an angle against the commutator. As in the other types, the carbons are connected to the holder by flexible leads.

The sliding type has several advantages. The small inertia of the carbons or moving parts enables the brushes to keep in intimate contact with the commutator, and makes this style of holder particularly adaptable to high-speed machines. The clamped type generally finds its best application where it is necessary to carry relatively large currents. With small carbons this type

Fig. 99.

permits of a cheap construction with relatively high efficiency. For commutator service it is inherently defective, owing to the inertia of the moving parts. This objection, however, is not so important when the brushes are small.

105. Brush Rigging.—In general, the brush holders are mounted on studs which are attached to but insulated from a suitable brush rigging which in large machines consists of two rings connected by radial cross arms as shown in Fig. 98. The larger ring is accurately fitted in a recess in the field yoke in which it may be shifted to secure proper brush position. A brush stud with a set of brushes is shown in Fig. 99. The brush studs are connected to two heavy rings of copper insulated from each other and from the rocker ring. The terminal cables or leads are connected to these bus rings, as is seen in Fig. 98.

On the smaller machines the brush rigging is usually mounted on the bearing and is held in place by a set screw.

Recapitulation

1. The armature of a direct-current dynamo is the rotating member in the conductors of which the electromotive force is induced.

2. The armature core is built up of stampings of sheet steel of high permeability. The planes of the laminations are at right angles to the shaft.

3. There are three sources of energy loss in the armature. These are eddy currents, hysteresis, and I^2R losses in the windings.

Eddy currents are produced by the armature core cutting the field flux. To reduce their effect the armature core is laminated.

The hysteresis loss is due to the reversal of magnetism in the armature core as it passes from beneath one pole under a pole of opposite polarity. In order that this loss may not become excessive the laminations are made of iron of high magnetic quality.

The losses due to the heating of the armature coils are kept small by using low-resistance windings.

4. The function of the commutator is to change the connections of the armature coils with the external circuit every time the current in the coils is reversed. Most of the prominent dynamo troubles manifest themselves at the commutator.

5. The drum-armature winding is the only type used on commercial machines. There are two main kinds of drum winding, the *lap winding* and the *wave winding.*

The *lap winding,* as its name implies, is a winding in which the successive turns of the coils lap back over each other.

The *wave winding* is a type of drum winding in which the successive elements progress continuously in the forward direction in a wave form around the circumference of the armature. *Wave* and *lap* windings are often called *series* and *parallel* windings respectively.

6. The number of sets of brushes for armatures with lap winding must be the same as the number of field poles.

For armatures with wave windings there may be as many sets of brushes as there are field poles, or there may be only two irrespective of the number of field poles.

7. The pressure between brushes of a multipolar generator is

$$E = \frac{p\Phi Zn}{q \times 60 \times 10^8}$$

when p, q, Φ, Z, and n have the significance given in Article 72.

8. Brushes for direct-current dynamos are usually made of some form of carbon. They are held against the commutator by springs which should exert a pressure of 1.5 to 2 pounds per square inch of contact area of the brush.

With the exception of motors which must be reversed often, it is the usual practice to set carbon brushes at a slight angle to the face of the commutator.

The current is conducted from the brush through a braided copper conductor, commonly called "pigtail," to the brush rigging.

CHAPTER IX

USES OF ELECTRICAL ENERGY

106. Introductory.—The output of an electrical generator may be used for such a variety of purposes that only a few of the most common applications will be enumerated here, and these will be explained primarily to show how the character of the application influences the design and characteristics of the electrical apparatus. In general, the industrial use of electrical energy may be classified under the following heads:

(*a*) Heating and lighting.

(*b*) Power.

(*c*) Electrolysis.

(*a*) *Heating.*—Under heating may properly be classed any and all conversions of electrical energy into heat which is then utilized. The simplest application is the conversion of the energy of an electrical current in or by means of a resistance in accordance with Joule's law. Examples are electrical stoves, heating devices, flat irons, etc. The conversion of electrical energy into light by means of the incandescent and arc lamps may also be classed as heating, for, in the main, the light is caused by raising the temperature of some body to incandescence, and the light produced is such a small per cent. of the total energy converted that it may be considered as a by-product from the viewpoint of energy conversion.

This, however, does not apply to the production of light in the mercury-vapor lamp or in the Moore vacuum-tube system.

The production of light in the mercury-vapor lamp is perhaps due to two causes, heating and some form of electro-luminescence. This is shown by the fact that the efficiency of the lamp is very high, ½ watt per candlepower, and is not affected by change in temperature. In the Moore vacuum tube the light is produced mainly by luminescence. Both heating and luminescence are factors of light production in the luminous arc lamps.

The use of the electric current in the electric furnace is also of vast industrial importance. While chemical combinations and

decompositions are produced in the electrical furnace, these changes are due mainly to temperature effects and not to electrochemical action as in the case of an electrolyte. The products of the electric furnace are numerous and are constantly increasing in importance.

(*b*) *Power.*—The conversion of electrical energy into mechanical energy by the action of an electric motor is so common that it need scarcely be mentioned. The ease with which energy, which is generated at a large central station or hydro-electric plant, may be transmitted to places where it is to be utilized, and the fact that the energy generated can easily be subdivided and by means of the electric motor it can be conveniently applied directly to a machine has resulted in important and wide applications of the dynamo. Thus the energy of the electric current is now used for the operation of the smallest as well as the largest machines. The electric motor drives not only the motors on street cars and tools in machine shops but all kinds of things—from appliances such as an egg-beater and a sewing machine up to the great battleship New Mexico.

In many instances the electric motor can be used to apply power more advantageously than the steam engine, and in other instances it can apply power for operations for which the steam engine is not suitable.

(*c*) *Electrolysis.*—The term electrolysis, as here used, refers to the process of dissociating chemical compounds by the electric current, such as electroplating, the manufacture of electrolytic compounds, and the electrolytic recovery of ores.

107. Distribution Systems.—For the purpose of conveying electrical energy from its source to the apparatus where it is to be utilized, a system of conductors is required. Such a system of conductors which electrically connects the generating station with the receiving apparatus is called a distribution system. Direct-current distribution systems are chiefly of two kinds:

(*a*) Series.

(*b*) Parallel.

(*a*) *Series System.*—The first device for the conversion of electrical energy into light was the arc lamp. It was also the only device that was to be connected to the generator, hence the simplest arrangement of the lamps was employed. The lamps were connected so that the current passed successively from the positive terminal of the generator through all of the lamps in

series to the negative terminal, Fig. 100. This is known as the series system of distribution. It is very evident that only lamps of the same current capacity could be connected in series and that for efficient operation the current should remain constant.

The electrical pressure on a series system diminishes throughout the entire circuit in direct proportion to the resistance and the number of lamps in the circuit. Hence, when one lamp is either connected to or disconnected from such a circuit, the pressure at the generator required to send the current through the remaining lamps is different and accordingly the generator pressure must be varied. The generators required to furnish current for such a circuit had to be designed so as to automatically vary the voltage over a wide range and yet have a constant current output. Direct-current generators of this type are not used to any great extent at present. Where a series circuit of any extent is used the current supplied is usually alternating, and the

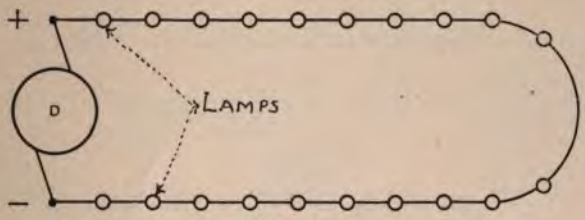


FIG. 100.

current is maintained constant by a suitable transformer. The series circuit in this country is used almost exclusively for street lighting.

(*b*) *Parallel Circuits.*—As the number of devices to be operated electrically increased, it became impossible to supply each device from a special generator, and hence, in order that each device might be operated independently and at the proper voltage a different system of connections was devised. This system is known as the parallel, or multiple system, Fig. 101. There are two types of parallel circuits in use, the *two-wire* and the *three-wire.*

In the series system the voltage at the generator had to be equal to the pressure across one lamp multiplied by the number of lamps plus the voltage drop in the wires, terminals, etc. The generator thus operated at a comparatively high voltage. For

house lighting, the arc lamp is too large a unit and the introduction of such high voltages into houses is dangerous.

The parallel or multiple system was adopted for incandescent lighting because of the necessity of operating the lamps at low pressure and of the comparative ease of control. The voltage was fixed at about 110 volts by the nature of the carbon filament of the early incandescent lamp, which could not be made to give 16 candlepower at a much lower voltage without reducing its life.

The great variation in the light produced by slight fluctuations in the voltage at the terminals of the incandescent lamp necessitated the application of constant pressure, and accordingly constant potential dynamos were developed. At present nearly

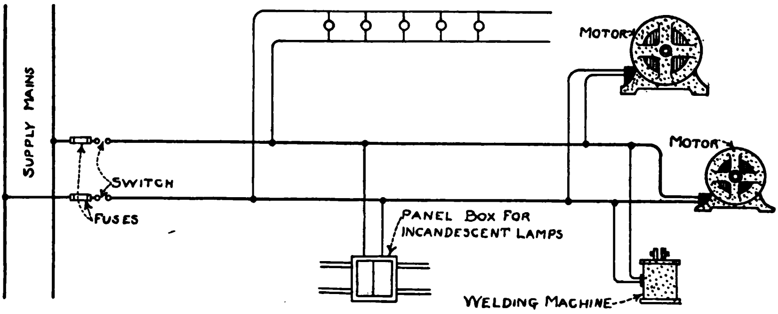


FIG. 101.

all generators are designed to give practically constant pressure. In general it may be said that the constant-current generator has been used almost without exception to supply current to series lighting circuits which formerly consisted of arc lamps exclusively. With the development of the tungsten lamp both for series and parallel operation the old carbon arc lamp is rapidly being displaced. The flaming carbon arc and the metallic arc lamps will undoubtedly continue to be used for some time to come. The former may be used on either direct- or alternating-current circuits while the latter is suitable for direct-current circuits only. But the current in either case is usually supplied by an alternating-current generator, and for the metallic arc lamp, it is rectified.

Most motor work, whether for factories, crane service, elevator service, electric railways, or numerous other uses, requires practically a constant pressure at the terminals of the motors.

Electroplating vats, while they usually require approximately a constant current, are usually connected to be operated from a constant-potential dynamo.

Storage cells are usually connected with a sufficient number in series so that the normal voltage of the battery will approximately equal the voltage of the machine to which they are connected. The change of voltage of the battery with the charge is taken care of by the use of end cell switches or some equivalent device.

Each of the above classes of service calls for a constant-potential supply system. An absolutely constant-potential system is never found in practice but the term is usually applied to any system where an attempt is made to maintain the potential at a constant value. Owing to the fact that a small change of pressure has a marked effect on the light given by an incandescent lamp and the life of the lamp, as well as on the satisfactory operation of other apparatus of the system, it is extremely desirable to maintain the pressure on such a system as nearly as possible at a constant value. For incandescent lighting the pressure should be kept at all times within 3 per cent. of the normal rating of the system. The methods of maintaining constant voltage will be discussed later in connection with the various types of dynamos.

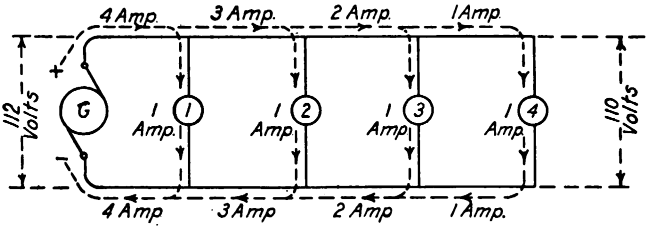


FIG. 102.

108. Two-wire Parallel Circuit.—The two-wire circuit is represented in Fig. 102. *G* is the generator which supplies current at constant voltage to the lamps which are connected in parallel across the two line wires. When such a connection is employed, the current in the mains is equal to the sum of the currents in the lamps. If many lamps are connected to such a circuit, the mains will have to be large in order to keep the voltage drop within reasonable limits, that is, the amount of copper used for

conductors is large. The low voltage two-wire circuit is thus suitable for only comparatively short distances.

109. Three-wire Parallel Circuit.—To extend the distance over a wider territory than was economically possible by the two-wire system there was proposed simultaneously by Edison in this country and by Hopkinson in England, a modification termed the three-wire system. Fig. 103 shows the essential features of such a system. A and B are two similar generators connected in series. The voltage between the outside mains is twice the voltage of either generator. The advantages of the three-wire system of power distribution lie mainly in the fact that a higher voltage may be used and thus the same power may be transmitted over smaller wires than in the two-wire system.

From Fig. 103 it will be evident that if lamps 1 and 2 are alike and both are turned on, the current will flow through the two lamps in series and therefore there will be no current flowing in the middle wire or "neutral." Likewise in Fig. 104, if the lamps in both sets are alike, and for every lamp turned on in set A, the lamp in series with it in set B is turned on, there will be no current flowing in the neutral. The system will then be the equivalent of a 220-volt two-wire system with a number of 110-volt lamps connected two in series between the 220-volt mains.

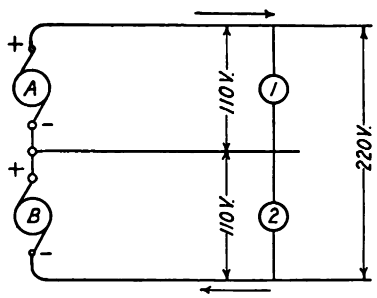


FIG. 103.

Again in Fig. 104 when a number of lamps in each set are turned on so that the same amount of current is required by the lamps of set B as by the lamps of set A, there will be no current flowing in the neutral between E and F, but there may be some current in part or all of the section of the neutral between C and E. Suppose all the lamps of set A are turned on except No. 11, and all of the lamps of set B are turned on except No. 10. In this case the same number of lamps are turned on in each set, and as the lamps are all alike each set will require the same current and, therefore, there will be no current flowing in the neutral between E and F, but the current flowing through

lamp No. 9 will flow through the neutral from D to C, and then through lamp No. 12.

Balanced Load.—When the lamps in operation on each side of the neutral require the same current and there is no current flowing to or from the generators through the neutral, the load is said to be balanced. It will be noted from the above that in order to have a balanced load it is not necessary to have the lamps of the same rating, neither is it necessary to have the same number of lamps on each side of the neutral; the only requirement being that the lamps in operation on each side of the neutral take the same current.

Unbalanced Load.—It can not be expected that a balanced load, such as has been described above, will always exist, in fact,

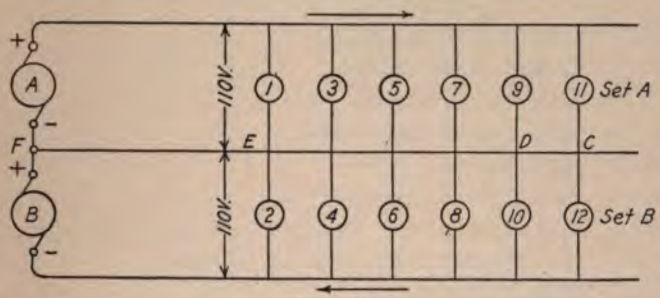


FIG. 104.

it seldom exists. In case the load is unbalanced, that is, equal currents are not required by the lamps on each side of the neutral, the neutral will carry the difference in currents.

In Fig. 103 if only lamp 1 is turned on, the current will flow out through the upper wire and back to the generator through the neutral. If only lamp 2 is turned on the current will flow out through the neutral and back to the generator through the lower wire. In the first case, only generator A will be supplying current, and in the second case, only generator B will be supplying current.

In Fig. 104 if lamps Nos. 1, 2, and 3 each requiring 1 ampere are turned on, 2 amperes will flow to the lamps through the upper wire; the current will then divide and go through lamps 1 and 3 and will come together again at E where it will again divide, half of it going to lamp 2 and the other half returning through the neutral to the generator.

110. Voltage Drop in Three-wire Systems.—The voltage at the lamps in a three-wire system is not the same as at the generators. When the load is balanced, there is a voltage drop in the two outside conductors and the pressure across both lamps is diminished by this voltage drop. The pressures across each of the two sets of lamps are the same and equal to one-half the difference between the two generator voltages and the voltage drop. When the load is unbalanced the current in the neutral also produces a voltage drop which modifies considerably the division of the applied pressures. This voltage at the lamps, when that at the generators is given, can be calculated by the aid of Kirchoff's laws which have been explained in a preceding chapter. To apply these laws to the determination of the voltage at the lamps let us assume the following general conditions:

I_1 = current in upper main,
I_0 = current in the neutral,
I_2 = current in the lower main,
R_1 = resistance of upper main,
R_0 = resistance of neutral,
R_2 = resistance of the lower main,
R_A = joint resistance of the A set of lamps, Fig. 104,
R_B = joint resistance of the B set of lamps,
E_A = voltage of generator A,
and E_B = voltage of generator B.

Then $I_1 + I_2 + I_0 = 0$, by Kirchoff's first law.

By the second law we have

$$E_A = I_1R_1 + I_1R_A \mp I_0R_0$$

and

$$E_B = \pm I_0R_0 + I_2R_B + I_2R_2$$

which gives

$$I_1R_A = E_A - I_1R_1 \pm I_0R_0 \text{ for set } A$$

and

$$I_2R_B = E_B - I_2R_2 \mp I_0R_0 \text{ for set } B.$$

The sign to be prefixed to I_0R_0 will depend upon the balance of the load. When the load is unbalanced and $I_1 > I_2$, $I_1 = I_2 + I_0$, and when $I_2 > I_1$, $I_2 = I_1 + I_0$. Hence when the term I_0R_0 is positive for one set it is negative for the other set and *vice versa*. The equations thus show that the pressure at one set of lamps is diminished by the voltage drop in the neutral, and in the

other set it is increased by the same amount. An example will serve to make this more easily understood. Different means employed to secure equal voltages between neutral and outside wires will be explained in connection with three-wire generators.

EXAMPLE

A three-wire circuit supplies 500 lamps each taking ½ ampere; 275 lamps being on one side of the neutral and 225 on the other side, all at a distance of 1,000 feet from a 231-volt three-wire generator. The voltage between the neutral and either outside main is maintained at 115.5 volts at the generator. The outside wires are of No. 0000 A.w.g. copper wire and the neutral consists of No. 0 wire. Find the voltage across each set of lamps.

Solution.—

$$\begin{aligned} I_1 &= 275 \times \tfrac{1}{2} = 137.5 \text{ amperes.} \\ I_2 &= 225 \times \tfrac{1}{2} = 112.5 \text{ amperes.} \\ I_0 &= 137.5 - 112.5 = 25 \text{ amperes.} \\ R_1 &= 0.05 \text{ ohm at } 25°\text{C.} \\ R_0 &= 0.1 \text{ ohm at } 25°\text{C.} \\ R_2 &= R_1 = 0.05 \text{ ohm.} \end{aligned}$$

Since $I_1 = I_2 + I_0$, we have

$$\begin{aligned} I_1R_A &= E_A - I_1R_1 - I_0R_0 \\ &= 115.5 - 137.5 \times 0.05 - 25 \times 0.1 \\ &= 115.5 - 6.875 - 2.5 \\ &= 115.5 - 9.375 \\ &= 106.125 \text{ volts} \end{aligned}$$

and

$$\begin{aligned} I_2R_B &= E_B - I_2R_2 + I_0R_0 \\ &= 115.5 - 112.5 \times 0.05 + 25 \times 0.1 \\ &= 115.5 - 5.625 + 2.5 \\ &= 115.5 - 3.125 \\ &= 112.375 \text{ volts.} \end{aligned}$$

111. Advantages of Three-wire Systems.—The advantage of the three-wire system is found in the reduced amount of copper necessary to deliver a specified amount of energy. Assuming a balanced load it can easily be shown that for the same voltage drop, and with the neutral wire of the same size as the outer wires, only three-fourths as much copper by weight is needed for the three-wire system as for the two-wire system. For the same percentage drop in voltage the amount of copper needed is reduced to three-eighths. In short, under the first condition there is a saving of 25 per cent. and in the second case a saving of 62.5 per cent. of copper results.

Recapitulation

1. Electrical energy is used for a variety of purposes; these may be classified under the following general heads:

(*a*) Heating and lighting.

(*b*) Power.

(*c*) Electrolysis.

2. All the devices for the utilization of electrical energy require for their operation either constant current or constant pressure. To meet these requirements we have constant-current and constant-potential dynamos. Nearly all electrical appliances are now operated from constant-potential generators.

3. There are two general types of distribution systems, the *series* system and the *parallel* system.

In the *series distribution system* all of the current-consuming devices are connected so that the same current flows through each. Thus consuming devices of the same current capacity can be operated in series.

In the *parallel distribution system* the current-consuming devices are connected in parallel across the supply wires. For parallel operation the consuming devices must be designed for the same voltage, but each may have a different current capacity.

4. Parallel distribution systems are of two kinds—two-wire and three-wire. The advantage of the three-wire system over the two-wire system is that it makes possible economical distribution of electrical energy over greater distances.

CHAPTER X

TYPES OF DYNAMOS

112. Excitation of Dynamos.—While the magnetic and electrical principles are the same in all direct-current dynamos, the service requirements are such that machines with different operating characteristics have been developed. The different types of generators and motors are differentiated from each other by methods of excitation, that is, by the manner in which the current for the field magnet coils is supplied and the manner in which these coils are connected to the armature and external circuit. The common methods of excitation are:

(*a*) Separate.
(*b*) Shunt.
(*c*) Series.
(*d*) Compound.

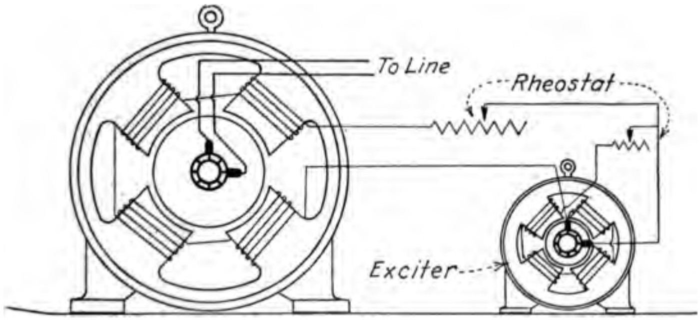


Fig. 105.

(*a*) *Separate Excitation.*—A dynamo is said to be separately excited when the source of field current is different from that of the armature. A generator is said to be separately excited when the magnetic field is excited from some outside source. A motor is separately excited when the current for the field coils and that for the armature come from different sources, Fig. 105. This method of excitation is used to a very limited extent on direct-current dynamos; on direct-current generators it is never used,

and on motors very seldom. Alternators, on the other h
are usually separately excited.

(b) *Shunt Excitation.*—A shunt-excited dynamo is one
which the field circuit and armature circuit are connecte
parallel if the dynamo operates as a motor. The connect
are exactly the same for motor or generator, but as the so
of the exciting current is the armature when the machine is o
ated as a generator, the field circuit is then in series with the ar
ture and in parallel with the load circuit. Sketch, Fig.
shows how the shunt field is connected. If the dynamo is o
ated as a generator, the current from the armature enters
field circuit at A and after circulating through the field win
reenters the armature at the other brush, B. By means of

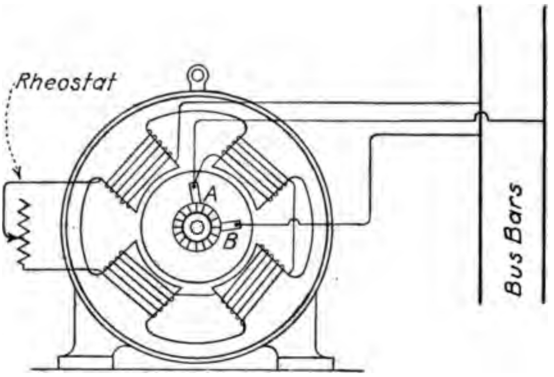


FIG. 106.

rheostat the current through the field winding is regulated.
shunt-field winding consists of many turns of comparati
small wire. The resistance is high as compared with the re
ance of the other circuits of the dynamo. The field curren
equal to the terminal voltage divided by the resistance of
field winding and the rheostat. In algebraic symbols, if
the terminal voltage,

$$I_f = \frac{E}{R_f + R}$$

where R_f is the field winding resistance, and R is the rheo
resistance which is variable. R_f is comparatively high, henc
is relatively low, but, owing to the many turns in the wind
the magnetomotive force is sufficient to develop the desired f

If R_a is the armature resistance, the terminal pressure is $E = E_0 - IR_a$, where E_0 is the electromotive force induced; E will vary with the load. R_a is small, however, and hence the variation in terminal voltage due to this cause is comparatively small. The energy loss in the shunt field is $I_f^2(R_f + R)$. In order that this may be small, R_f is large and I_f is small.

(*c*) *Series Excitation.*—The first self-excited dynamo to be developed was the series dynamo. In this type of dynamo the field windings which produce the excitation are connected in a continuous path or circuit with the armature and the external circuit of the machine. Fig. 107 gives a diagrammatic view of such connections. In this case the current flows from the positive brush of the machine through the field coils, then to the external circuit, and back to the negative brush. The circuit then consists of the armature, field, and external circuit. Since these are all connected in series, the value of the current in each part is the same. The pressure E expended in the total circuit is absorbed as follows: IR is the drop through the external circuit if the external load consists of resistance only; IR_f is the drop in the field windings; and IR_a is the voltage drop in the armature. R_f and R_a are the resistance of field and armature windings respectively. The total pressure E_0 is then equal to:

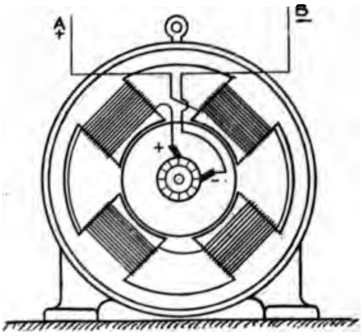


Fig. 107.

$$E_0 = IR + IR_f + IR_a$$

or

$$E_0 = I(R + R_f + R_a).$$

If R is not known, we may express IR by E and thus get:

$$E_0 = E + I(R_f + R_a).$$

The armature and field resistance of a series machine should be as small as possible in order to reduce to a minimum the losses within the machine. It has been shown that the heat loss due to resistance within any circuit is proportional to I^2R. It is

evident, then, that a large value of R will cause a large p
the energy of the current to be lost as heat. This will hav
harmful effects: First, the energy loss will decrease the effi
of the machine; and second, the large amount of heat will
an excessive rise in the temperature of the windings.

(*d*) *Compound Excitation.*—For compound excitation t
namo contains both a series and a shunt winding. Fig. 108
the winding as ordinarily applied to this type of machine.
shunt winding consists of many turns of fine wire as in the r
shunt machine, while the series winding consists of a few
of large wire. In the compound-wound dynamo, the shunt
ing may be considered as furnishing a certain initial flux,
the compound winding reinforces or opposes the action
shunt magnetomotive force, depending upon the charact
desired. There are thu
types of compound win
the *cumulative* and the *di
tial.* There is no differe
the mechanical construct
the two windings, the diff
being in their connection
armature.

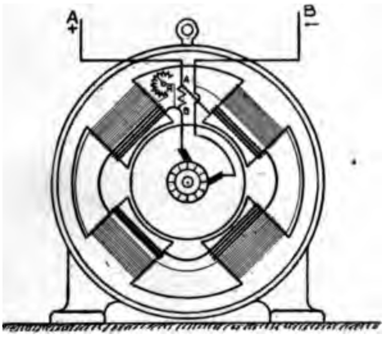


FIG. 108.

In the cumulative com
winding the magnetomotiv
of the series winding is
same direction as that
shunt winding, while in the
ential compound winding the two magnetomotive forces
each other. Cumulative compounding is employed on mo
tral-station direct-current generators and motors. The di
tial winding is little used. At present it is practically l
to generators used on automobiles for charging the storag
tery. A generator for this class of service must furnish
tically a constant current or rather the current must not
a certain value, while the speed varies through a wide
The electromotive force of a shunt generator under such
ditions would vary greatly, increasing and decreasing wi
speed but at a higher rate. To keep the electromotive for
thus the current from exceeding a predetermined value, a
ential winding is sometimes employed. The current th
the series coils demagnetizes the field as the speed increases

preventing the electromotive force from rising to an excessive value. The differential compound motor is no longer used.

It is not necessary in most machines to send all of the line current through the series winding. A few turns of wire are passed around the field poles and the two points A and B, Fig. 108, are connected by a German silver shunt. The line current divides, part of it going through the shunt and part through the series coils. When the machine is tested, the length of this shunt is adjusted to secure the proper degree of compounding.

Recapitulation

1. Direct-current dynamos are classified in accordance with the means of excitation employed. This basis of classification gives the following types of dynamos:

(a) Separately excited dynamos.
(b) Shunt dynamos.
(c) Series dynamos.
(d) Compound dynamos.

2. *The separately excited dynamo* is one in which the source of field current is different from that of the armature.

The *shunt dynamo* is one in which the armature circuit and field circuit are connected in parallel when the machine is operated as a motor, and the field circuit and load circuit are connected in parallel when the machine is operated as a generator.

The *series dynamo* is one in which the armature circuit and field circuit are in series, and the two are also in series with the load circuit.

The *compound dynamo* is one employing both shunt and series excitation. There are two types of compound dynamos, namely the cumulative compound and the differential compound.

In the *cumulative compound* method of excitation, the magnetomotive force of the series winding reinforces the magnetomotive force of the shunt winding.

In the *differential compound* method of excitation the magnetomotive force of the series winding opposes the magnetomotive force of the shunt winding. The differential winding is seldom used.

3. The armature resistance of all dynamos is very small. The resistance of the series windings is also very low. The resistance of the shunt winding is, however, comparatively high. The exact value of the resistance is in each case determined by the voltage and capacity of the machine.

CHAPTER XI

COMMUTATION

113. Definition.—In Article 29 it was shown that when the armature rotates an alternating electromotive force is induced in the inductors, and that in order to have a current flowing continuously in one direction in the load circuit it is necessary to interchange the connections of the armature inductors with the external circuit every time the electromotive force in the inductor is reversed. This rectification of the alternating armature current is known as commutation. To secure this interchange of connection of armature inductors and external circuit with the least possible disturbance requires great care and experience in design.

114. Elements of Commutation.—By reference to Fig. 83 it is evident that the current flow under the pole-face is continuously

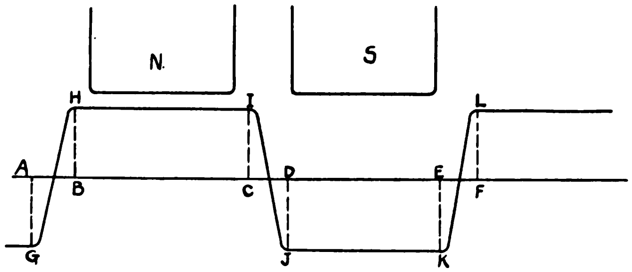


FIG. 109.

in one direction under a north pole and in the opposite direction under a south pole. As the current enters the armature at the negative brush it divides and flows by two paths through the armature coils finally returning by two paths to the positive brush. The current strength is the same in all of the inductors except those undergoing commutation. The length of the line BH, Fig. 109, represents the current strength in the armature inductors. If at the instant represented by the point B, the commutator segment severs or breaks contact with one brush, at that instant it must carry the current flowing in the other

inductors with which it is connected in series. This intensity or strength of current is represented by BH. So long as the load remains constant the current in the inductor will remain constant until the commutator segment comes into contact with the next brush at the point C. During the interval of time required for the conductor to pass from C to D the current should drop to zero, reverse, and attain an equal intensity in the opposite direction. Were such a condition attained in practice the performance of the machine, with respect to commutation, would be

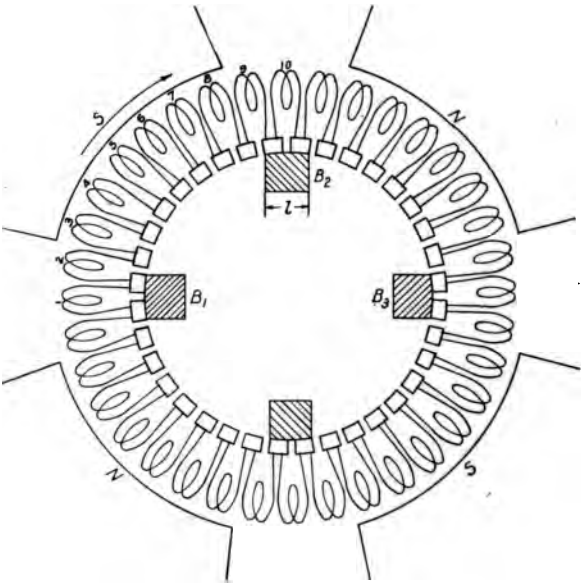


FIG. 110.

perfect. There are several factors, however, which modify these conditions and which must be considered.

115. Factors Affecting Commutation.—The factors that mainly affect the completeness of commutation are the inductance of the coil undergoing commutation, armature reactions with varying load, resistance of the brushes and brush contacts, width of brushes, and air gap. The effect of each of these will be considered somewhat more in detail.

116. Inductance of Armature Coil.—For simplicity let us consider a ring armature as shown in Fig. 110. The electromotive force generated in coil 1 when in contact with brush B_1,

is practically zero, unless there is considerable interpolar flux, which for the present will be neglected. As the coil rotates toward the right this electromotive force rises and reaches a maximum when it reaches the position occupied by coils 5 and 6 in the figure, or about midway between the brushes B_1 and B_2. The electromotive force then decreases and reaches zero again, when the coil enters the interpolar space and occupies the position of coils 9 or 10. This fluctuation of voltage has already been fully explained. The current in this coil is, however, constant from the time it leaves the brush B_1 until it again makes connection with brush B_2. This has been explained in connection with Fig. 109. The current in the coil must reverse during the interval of time required for the insulation A, Fig. 111, to pass across the brush.

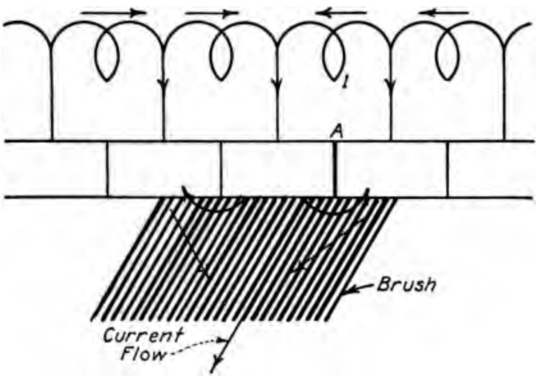


FIG. 111.

During this interval of time the current must change from $+I$ to $-I$ or a total change of $2I$. The rate of change of current is then $\frac{2I}{t}$ where t represents the time interval. If L is the inductance of the coil, the electromotive force of self-inductance will be $\frac{2I}{t} \times L$. This is on the assumption that the rate of change is uniform, or that the current change is properly represented by the line IJ, Fig. 109. The energy of the magnetic field due to the current I must be dissipated and an equal amount stored when the current is reversed. This is a total change of energy equal to LI^2. If L is appreciable and if the duration of commutation is very brief, the rate at which this energy must be changed will be high and bad commutation will result. As a matter of fact the

change of current during commutation is much more comp than that assumed. The moment the coil is short-circuited the brush, the current begins to die out at a rate depending up the resistance of the coil, contact resistance of the brush, t inductance of the coil, and the rate and direction at which it cutting the field flux. The higher the resistance of the coil a brush, the more rapid the change of current, and the higher t inductance L the slower the change of current. If the field fl cut is in such a direction that the induced electromotive foı opposes the electromotive force of self-induction, the rate change will also be higher. Thus with respect to the relati effect of these factors good commutation is obtained in t ways which are known as *resistance commutation* and *volt commutation.*

117. Resistance Commutation.—If the armature coil underg ing commutation is in the magnetically neutral plane, no flux being cut and hence no electromotive force, except that of se induction, is induced. Under such conditions the commutati is entirely determined by the inductance and resistance of t armature coil, brushes, and brush contacts. Where the elect motive force of self-induction is negligible, low-resistance brusl may be used, otherwise a comparatively high-resistance bru and brush contact are necessary. It is the high contact resi ance of the carbon brush that is of importance in commutati This contact resistance decreases with the load current, or put another way, the voltage drop between brush and commuta increases very slowly with very considerable increase in curre density so long as the brush pressure remains constant. T reduction in the contact resistance with increase in current d sity is in some respects a disadvantage. For instance, as the lo or working current increases, the electromotive force of se induction also increases, and if at the same time the contact sistance is reduced it is evident that much higher local curre will flow. Under certain conditions when the voltage betwe the commutator segments is 2 volts the brush contact resista may limit the local current to 20 amperes per square inch contact area. If, however, the voltage between commuta segments should be increased 50 per cent., then a local curre of possibly 150 to 200 amperes per square inch may flow, a this excessive current density may destroy the brush conta This disadvantage can not be satisfactorily remedied by the

of brushes of high resistance, for as the brushes are also in the path of the load current any increase in this path will increase the losses. A compromise must therefore be adopted. In some machines, a low-resistance brush is practicable, with consequent low loss due to working current. In other cases higher-resistance brushes give better average results.[1]

118. Voltage Commutation.—When the armature coil undergoing commutation is cutting a magnetic field in a direction such that the electromotive force generated by the rotation opposes the electromotive force of self-inductance, the local short-circuited currents may be kept within safe limits. This is accomplished by shifting the brushes forward on a generator or backward on a motor so that the coil when undergoing commutation is cutting flux under the following, or preceding, pole. Another means of securing good voltage commutation is the use of the commutating pole which will be explained later. In practice a combination of the two methods of commutation is employed.

119. Armature Reactions, Definitions.—The direct-current dynamo has two interconnected electrical circuits—the armature and field windings. When carrying currents each of these circuits sets up a magnetomotive force which tends to set up an independent magnetic field. As a consequence there results a composite or resultant magnetic field which differs in strength and position from that produced by the field windings only. This change in the strength and distribution of the excitation field, caused by the armature magnetomotive force, is called *armature reaction.*

120. Cause and Effect of Armature Reaction.—The cause and effect of armature reaction will, perhaps, be more readily understood if we consider what takes place when a current-carrying coil is placed in a uniform magnetic field. The distribution of the magnetic flux around and through such a coil when no external magnetic field is present is shown in Fig. 112. When the plane of such a coil is placed at right angles to a uniform magnetic field a composite field results, Fig. 113. This composite field is stronger or denser on the inside of the coil where the two magnetomotive forces act in the same direction, than on the outside where they oppose each other.

A similar phenomenon takes place when the magnetic field of the field windings and that of the armature are superposed or

[1] B. G. Lamme, *Electric Journal,* Vol. 13.

combined. Fig. 114 shows the distribution of the magnetic flux across the air gap of a two-pole field when no current is flowing in the armature windings. It will be observed that the magnetic lines are symmetrically distributed throughout the air gap and armature core. The distribution of this flux, under the con-

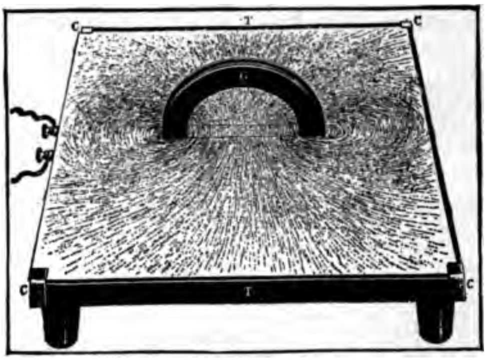


FIG. 112.

ditions assumed, is shown graphically in Fig. 115. Under the pole-face the flux density is uniform. In the interpolar space the flux density decreases very rapidly. The point where the flux density at the armature surface is zero is called the magnetic neutral point. The line joining the neutral point with the center

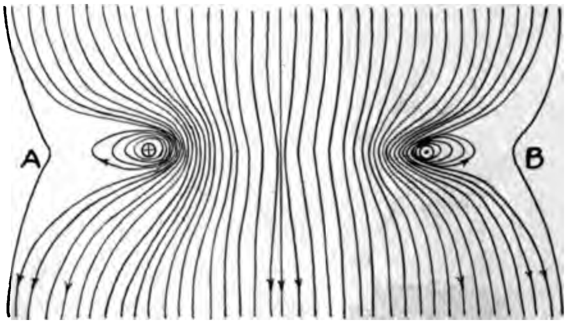


FIG. 113.

of the armature is called the neutral axis. Such a line is bb', Fig. 114.

If no current flows through the field windings, but a current is sent through the armature, the flux distribution will be as shown in Fig. 116. In this figure the brushes are assumed to be midway

between the poles. When so placed the current flows away from the observer on one side of the armature and toward the observer on the other side. The conductors in which the current flows

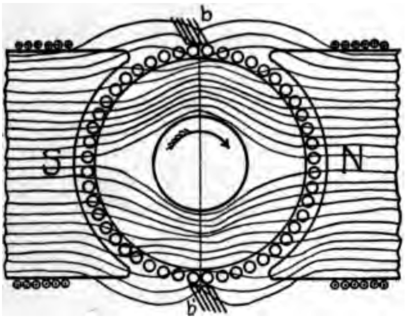


FIG. 114.

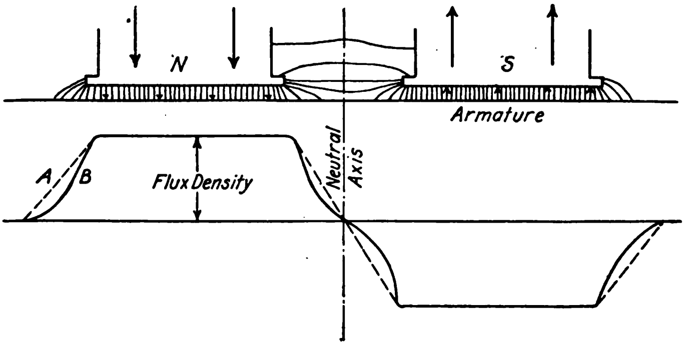


FIG. 115.

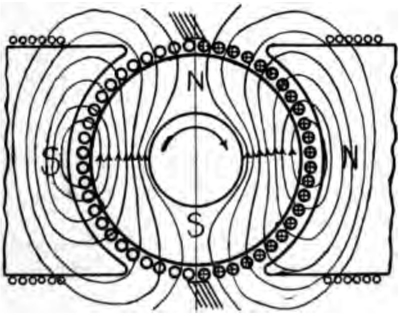


FIG. 116.

away from the observer are marked ⊕ and those by which the current returns are marked ⊙. The result of such a current distribution and flow is a north magnetic pole at the top and a

south magnetic pole at the bottom of the armature. It is very evident that the direction of this field is at right angles to that produced by the field exciting current.

If the field be excited at the same time, these two magnetic fields will be combined and there will result a distorted magnetic

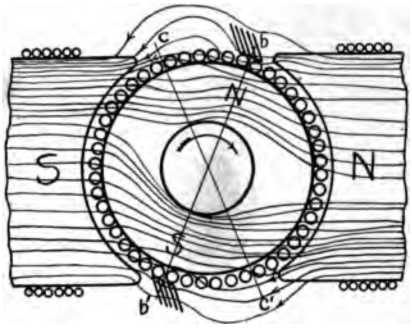


FIG. 117.

field as shown in Fig. 117. The resultant flux is no longer uniformly distributed under the pole-face, but the density increases from one side to the other in the direction of rotation if the ma-

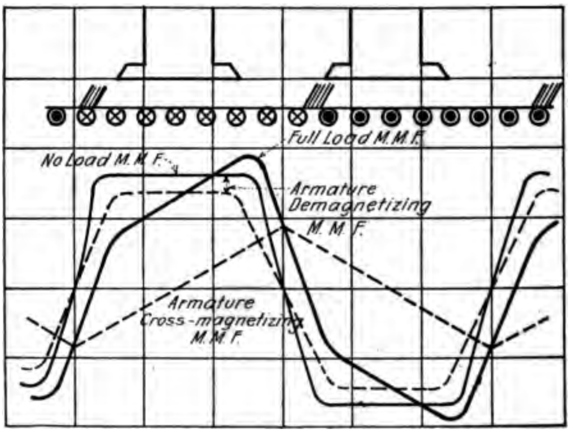


FIG. 118.

chine is a generator. This unequal distribution is shown graphically in Fig. 118.

When a machine is operating on no load and there is no field distortion the flux is evenly distributed as shown in Fig. 114, and

the neutral line is at right angles to the main field and the brushes are located at b and b'. With an armature with straight end connections or when the armature has spiral connections, the brushes would be set so that the coils being commutated lie midway between the poles.

The effect of the armature reaction mentioned above is to shift the main field, as shown in Fig. 117, so that the neutral line is shifted in the direction of rotation or in a forward direction as shown by bb' and, in order to secure sparkless commutation, it is necessary to give the brushes a forward lead. The brushes would then be in a position corresponding to bb', Fig. 117, instead of at bb', Fig. 114. We may now consider the armature winding divided into four belts. If we assume the connections such that the conductors between b and c' are connected across to those

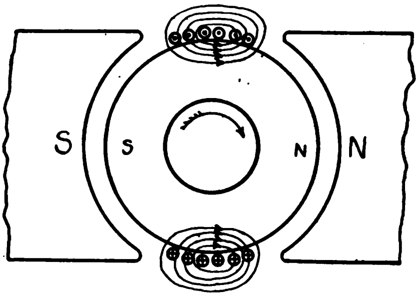


FIG. 119.

between c and b', we will have a winding which will set up a magnetizing force in the direction shown in Fig. 116 at right angles to the main field. The ampere-turns in this section of the winding are called the *cross-magnetizing ampere-turns.* Suppose the conductors between c and b, Fig. 117, are connected to those between b' and c'; we have the ampere-turns in this belt producing a magnetizing force exactly opposed to that of the main field as shown in Fig. 119. These are called the *demagnetizing ampere-turns.*

The combined effect of the separate magnetomotive forces may be shown graphically as in Fig. 120. Let the length and direction of OA represent the magnitude and direction respectively of the magnetomotive force of the field windings. Similarly let OB represent the magnitude and direction of the magnetomotive force of the cross-magnetizing turns of the armature

and OC that of the demagnetizing armature turns. This last-mentioned magnetomotive force is in direct opposition to that of the field windings. Combining these lines graphically, we have OD as the resultant armature magnetomotive force, and OR as the effective resultant of both the armature and field-current magnetomotive forces. A change in any of the components OA, OB, or OC will change both the magnitude and direction of the final resultant OR. As OB and OC change with the load current it is very evident that the effect of the armature reaction is not only to distort the field flux, but it also makes necessary the shifting of the brushes to the shifted neutral axis thus increasing the demagnetizing turns which reduce the flux produced.

In operation, the effects of armature reaction are manifest only in the character of commutation. The most common

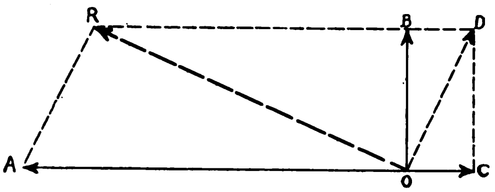


FIG. 120.

result of the excessive shifting of the neutral line with fixed brushes is constant sparking and "spitting" at the brushes. Extreme distortion results in excessive voltage between commutator segments which may cause flash-over although there are other contributory factors.[1]

Less apparent results are:

1. Blackening and burning of the commutator.
2. Excessive rise of temperature in commutator, due to excessive local currents.
3. Rough surface and reduced commutator life.
4. Rapid wear and deterioration of the brushes.

121. Abatement of Armature Reaction Effects.—Several different means have been employed to reduce the effect of armature reaction. In the earlier machines provision was made for rocking the brushes. Thus as the current in the armature increased the brushes were shifted in the direction of rotation on generators and in the opposite direction on motors.

[1] B. G. LAMME: *Proceedings* A. I. E. E., September, 1915.

Shifting the brushes forward shifts the plane of commutation in the same direction and the current flowing in any coil is not commutated until the coil is cutting magnetic lines in a reverse direction, so that the induced electromotive force counteracts the electromotive force of self-inductance.

In a motor the direction of current flow is against the induced electromotive force. Thus the brush that is positive when the machine operates as a generator becomes positive when the machine is operated as a motor. The effect of the reversal of

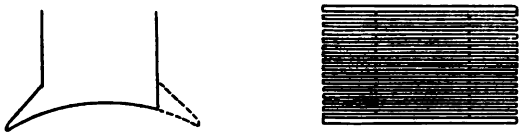


Fig. 121.

the direction of current flow in the armature is to shift or distort the magnetic field backward with reference to the direction of rotation of the armature. The brushes must, therefore, be rocked backward, that is against the direction of rotation, if the electromotive force induced in the coil by cutting magnetic lines is to oppose the electromotive force of self-induction.

Although rocking the brushes is a simple corrective it has some important limitations. In the first place, if the load fluctuated rapidly each machine would need a separate attendant, or else

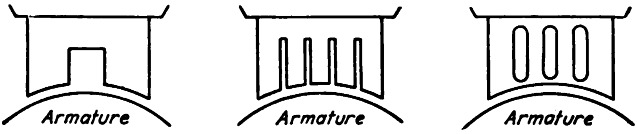


Fig. 122.

some automatic brush shifting device would have to be used. For motors which have to be reversed, such as railway motors, such an expedient is wholly inapplicable since the brushes would be in the wrong position every time the direction of rotation was reversed. In the second place, the shifting of the brushes from the magnetically neutral plane increases the distortion, the effect of which it is desired to correct. This effect is especially marked on machines with constant field excitation.

Another expedient adopted to limit the field distortion due to

armature reaction is to construct the pole pieces in such a way that the forward tip is saturated. For this purpose the pole-piece laminations are punched without tips at one end and then assembled with tips alternating from one side of the pole to the other, Fig. 121. By such a construction the area of the magnetic material near the armature is reduced and the flux density in the iron greatly increased. The field magnetomotive force required to produce the required flux is correspondingly higher and the same armature current can not as readily distort the field.

The practice of using a strong or "stiff" main field with a relatively high reluctance in the magnetic circuit is also exemplified in the slotted pole cores, some forms of which are shown in Fig. 122, and chamfered and eccentric poles, Fig. 123.

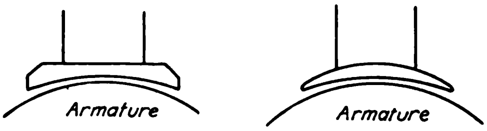


FIG. 123.

122. Compensation for Armature Reaction.—From Fig. 120 it is evident that the component OB is responsible for the distortion of the magnetic field. This cross-magnetizing component of the armature magnetomotive force makes necessary the shifting of the brushes which introduces the demagnetizing component OC. It is very evident, then, that if the cross-magnetizing effect of the armature current can be surpressed or balanced by an equal and opposite magnetomotive force the demagnetizing component will not develop and the brushes can be permanently left in one position. The balancing of the cross-magnetizing effect of the armature current is known as a compensation of armature reaction. It was shown that if the current is assumed to change at a uniform rate during commutation, the electromotive force of self-induction is given by $-\frac{2LI}{t}$, where t is the duration of the short-circuit of the armature coil by the brush. It is very evident that as the speed of rotation of the armature increases the time interval t decreases and hence at high speeds the electromotive force of self-induction is higher than at low speeds while the same current is being commutated. There are thus two elements in the problem of securing good commutation in

high-speed machines; one is the balancing of the cross-magnetizing effect of the armature current, and the other is the generation of an electromotive force in the coils which shall balance the electromotive force of self-induction. This in practice is accomplished by two closely allied means—one the compensating winding, and the other the interpole or commutating pole.

FIG. 124.

123. The Compensating Winding.—The compensating winding consists of coils imbedded in the pole-faces and connected in series with the armature. These coils are arranged and connected so that the magnetomotive force is equal in value and opposite in direction at all points around the armature to that produced by the current in the armature conductors. A good example of this type of winding is that designed by Thompson & Ryan and used by the Ridgway Dynamo and Engine Co., as shown in Fig. 124. The magnetic field cores without the winding

are shown in Fig. 65. The pole pieces consist of two parts, one part forms the core for the field coils and the other, the pole-face or pole shoe. The pole shoes are slotted and within these slots are wound the compensating coils. These coils lie parallel to the armature bars, but they are so connected that the current in them flows in the opposite direction to that in the armature bars directly under them. The magnetic field set up by the current in the compensating winding neutralizes or balances the cross-magnetizing effect of the armature current. As the load increases

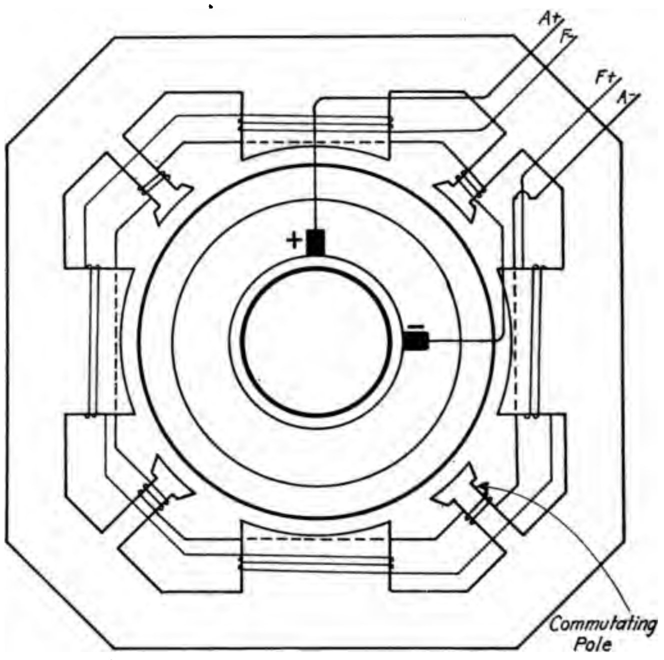


FIG. 125.

the neutralizing effect of the compensating coils increases proportionately and the commutating plane remains stationary.

124. The Interpole or Commutating Pole.—Commutating poles or interpoles in their usual form consist of a single piece of iron placed between the field poles, or in the plane of commutation, Fig. 125. The air gap, the shape of the pole, the direction of winding, and the number of turns are matters which require careful consideration. The magnetomotive force produced by the current in the commutating pole winding must be sufficient

to neutralize the armature magnetomotive force in the commutating zone, and in addition it must develop sufficient commutating flux to balance the electromotive force of self-induction in the commutated coil.

The effect of the commutating poles on the distribution of the magnetic lines under the poles and within the commutating zone is disclosed by Fig. 126. Curve *A* shows the flux distribution when no current is flowing in the armature. It is the field form produced by the shunt winding alone. Curve *B* shows the flux distribution with full load on the machine without the auxiliary

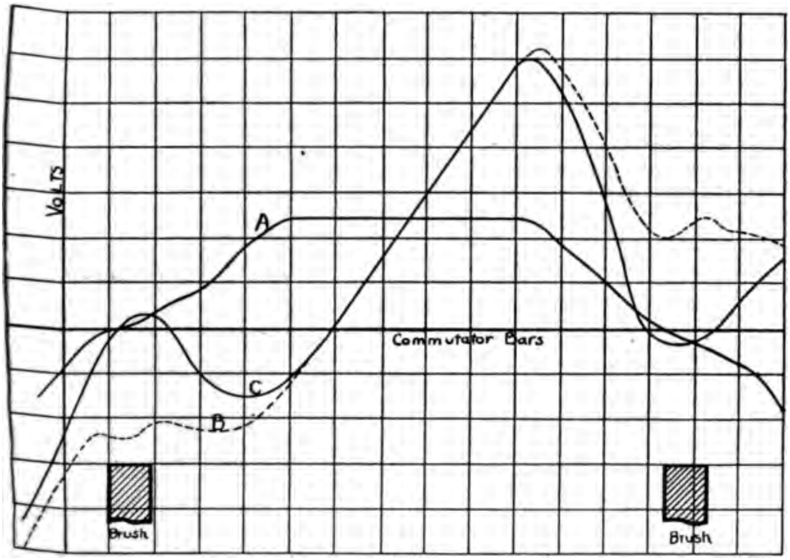


FIG. 126.

poles. This curve shows clearly the distorting effect of armature reaction. Curve *C* shows the flux distribution at full load with auxiliary poles excited. This shows very clearly that the cross-magnetization of the armature is still effective in distorting the field, but that the effect of armature reaction at the brushes has been completely neutralized. There is some compensation but it is not effective over the whole armature surface. When compensating coils are used as shown in Fig. 124 there is considerably less field distortion. This is shown in Fig. 127 which is the result obtained by combining both interpoles and a compensating winding as is done on the machine shown in Fig. 124.

The commutating poles are in this case excited by the compensating winding.

Commutating poles are especially of great advantage on variable-speed motors and on motors whose direction of rotation must be reversed. As the speed of a motor increases the rate at which the current in the commutated coil must reverse is increased. This increases the difficulty of commutation when no commutating poles are used. When commutating poles are used, any increase in speed results in a proportional increase in the commutating electromotive force which counteracts the electromotive force of self-induction due to high speed. The speed of a motor with interpoles may be varied through a wide range without serious sparking at the brushes.

Motors with commutating poles may be reversed with brushes fixed in the neutral position, for when the current in the armature

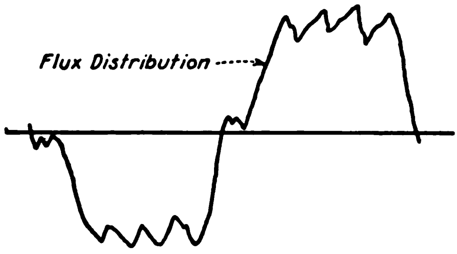


Fig. 127.

and interpole winding are reversed exactly similar operating conditions are obtained as in the forward direction. This action will be readily understood if the commutating pole be considered as the tip of the adjacent pole. In reversing the motor, since the current in the auxiliary winding is reversed, the interpole acts as the tip of the other adjacent pole. Exactly similar conditions, therefore, exist for either direction of rotation. Commutating poles are, therefore, of great advantage on railway motors.

Many generators are also built with interpoles, in fact, commutating poles are indispensable on direct-current turbo-generators. In most recent dynamos excessive distortion is prevented by some of the following methods: Proper proportioning of the field and armature ampere-turns, by designing for a strong field which is not readily distorted, by special forms of poles or pole

shoes. In this way the shifting of the field is kept within such narrow limits that the brushes are set permanently in the position of best commutation for all loads and the load can be varied from no load to 25 or 50 per cent. overload without serious sparking.

125. Flashing at Commutators.[1]—Under certain conditions of operation a direct-current dynamo may arc from brush to brush, or from brush to some other part of the machine, or a flash may originate between two adjacent commutator bars and it may not extend further or it may grow into a general flash-over.

The flash itself is merely an arc carried from one part of the machine to another by vaporized conducting material. The causes may be inherent in the machine or accidental. In any case they are likely to be quite complex. The fundamental cause in practically all cases is high voltage between commutator bars. The contributing or controlling causes are resistance of the armature winding, duration of commutation, current, character and condition of brushes. From many experiments Mr. Lamme concluded that the lower the resistance of the armature winding per bar, the lower would be the flashing voltage, and that 28 or 30 volts was approximately the lower limit, the results varying somewhat with the speed and with the load on the machine. The limiting voltage between bars on a loaded machine was found to be somewhat higher than on an unloaded machine.

Excessive overloads may cause flashing by giving high voltages in armature coil undergoing commutation. The excessively large resulting short-circuit current develops conducting vapor which is immediately carried forward producing flashing. If the current rush is not too great, the flash will usually appear only as a momentary blaze in front of the brush.

With respect to flashing, the machine with a compensating winding possesses some advantages over the straight commutating pole type. This advantage is due to the fact that the compensating winding usually secures better neutralization of armature magnetomotive force under extreme load conditions with resulting lower short-circuit currents in the brush contacts.

Recapitulation

1. By *commutation* is meant the converting of the alternating armature current into direct current in the external circuit.

[1] B. G. Lamme: *Proceedings* A. I. E. E., August, 1915.

2. The *primary factors* affecting commutation are: the inductance and resistance of the coil undergoing commutation; armature reaction; resistance of brush and brush contact; width of brushes and air gap.

3. By *resistance commutation* is meant the proper adjustment between the resistance of the brushes, brush contacts, and inductance of armature coils so that the armature current may die out and be reversed without sparking.

4. By *voltage commutation* is meant the development of an electromotive force in the coil undergoing commutation which will in a measure neutralize the electromotive force of self-inductance of the coil. This is secured by shifting the brushes and by the use of interpoles.

5. *Armature reaction* is the weakening and distorting effect produced by the armature current upon the magnetic flux produced by the exciting current in the field winding.

6. When the brushes on a dynamo are shifted, the effect of the armature current may be considered as the resultant of two magnetomotive forces—the *cross-magnetizing* and *demagnetizing* magnetomotive forces.

The *cross-magnetizing ampere-turns* develop a magnetic field at right angles to the main field.

The *demagnetizing ampere-turns* develop a magnetic field opposing the main field.

7. The *effect of armature* reaction is neutralized in several ways, the more common of which are:

The use of compensating windings.

The use of interpoles.

The use of large air gap and a "stiff" magnetic field.

Special design of pole faces and pole shoes.

8. The fundamental cause of *flashing* of direct-current dynamos is high voltage between commutator bars. The contributing or controlling causes are: resistance of the armature winding, duration of commutation, current strength, character and condition of brushes.

CHAPTER XII

OPERATING CHARACTERISTICS OF GENERATORS

126. Characteristic Curves, Definition.—To be able to select the machine which best fulfills the different requirements of service described in the preceding chapter it is necessary to know the behavior of the usual types of dynamos under different conditions. This characteristic behavior is best studied by the aid of curves which show how the various physical quantities involved in the operation of any machine are related. These curves are obtained by maintaining all conditions constant except those whose effects it is desired to determine. Thus one factor affecting the electromotive force of a generator is its excitation. The relation between exciting current and electromotive force at constant speed is called the *no-load characteristic*.

The terminal pressure does not depend only upon the speed and excitation, but also upon the amount and character of the load being supplied by the machine. Hence, another curve can be plotted between the terminal volts and the load current keeping speed and excitation current constant. Such a curve is called the *regulation* or *external characteristic.*

In some cases it is desirable to know how the current output of a generator varies with the resistance of the external circuit. Under such circumstances a curve plotted between current output, as ordinates, and resistance of the external circuit, as abscissas, gives what is called *ampere-ohm characteristic.*

When a dynamo is used as a motor the important quantities whose relations it is desirable to know are torque, speed, and current intake under different conditions of load. These quantities vary in certain characteristic ways depending upon the type of motor, and hence a curve showing the relation between any two of these is called a characteristic curve of the motor. The behavior or efficient operation of a dynamo can to a great extent be predetermined from the characteristic curves of the machine.

128. The No-load Characteristic of Separately Excited Generator.—This curve, sometimes called magnetization or satura-

tion curve, shows how the terminal voltage varies with a variation in the field exciting current while the speed of the armature is maintained constant at no load. As the electromotive force is given by $E = \frac{p\Phi Zn}{q \times 60 \times 10^8}$ it is evident that so long as n is maintaided constant E will vary with Φ; but as $\Phi = \frac{1.257NI}{\mathcal{R}}$ it evidently depends upon the ampere-turns of the field winding. The no-load characteristic then also shows the relation between

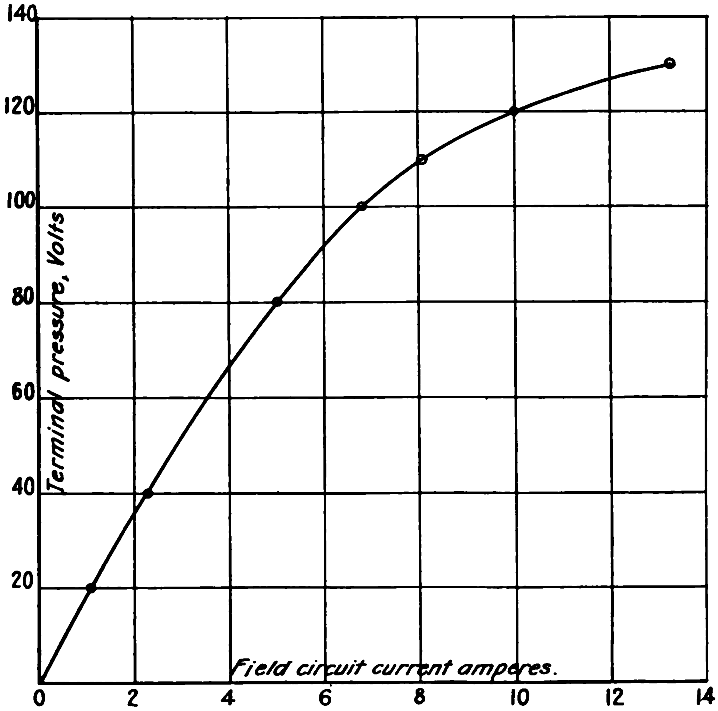


Fig. 128.

the magnetizing current and the resulting flux. It is, as above stated, sometimes called the magnetization curve. The curve is usually plotted with E as ordinates and I as abscissas, Fig. 128. The curve corresponds very well with the magnetization curve, Fig. 25, and shows that at constant speed and no load the terminal electromotive force increases rapidly at first and more slowly after a certain degree of field saturation has been reached. Owing to hysteresis, the magnetization curve

taken with decreasing field excitation will not coincide with the magnetization curve obtained with increasing field excitation but will be higher.

Direct-current shunt generators under normal operating conditions are excited to a flux density corresponding to a point above the bend of the magnetization curve, that is, to a point where the terminal voltage increases at a slower rate than the exciting current. This is necessary to secure stability or constancy in voltage. If the excitation were below the "knee" as the bend is called, a slight change in the exciting current would produce a great change in the terminal voltage. A generator which has been previously in operation will always retain a little magnetism

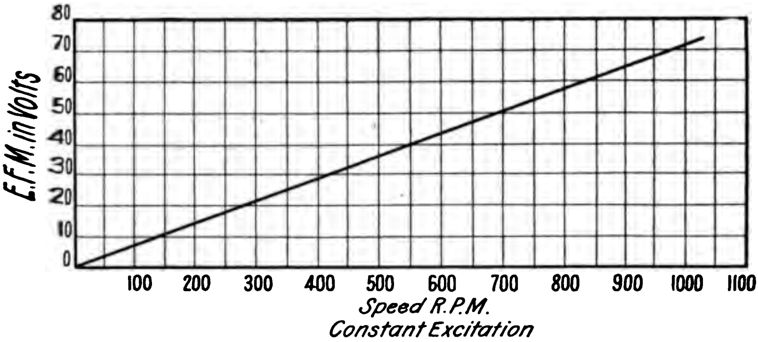


FIG. 129.

which will produce some electromotive force when the armature is driven at full speed. The magnetization curve for such a machine will not pass exactly through the origin but it will cross the electromotive force axis slightly above the origin.

The relation between the speed and voltage at constant excitation will give a straight line, as is evident from the fundamental electromotive force equation, namely,

$$E = \frac{p\Phi Zn}{q \times 60 \times 10^8}.$$

So long as Φ is constant, E will vary directly as n. Such a characteristic is shown in Fig. 129.

127. Experimental Determination of No-load Characteristics.—The diagram of connections for this test is shown in Fig. 130. The magnetic-field circuit is connected through a variable resistance rheostat to a source of direct current such as a storage

battery or other direct-current generator. An ammeter is connected in the field circuit and a voltmeter of suitable range is connected across the armature terminals. The armature must be driven at a constant speed. The procedure consists in varying the current through the field circuit by varying the resistance of the rheostat by suitable steps, and for every value of the field current the voltmeter reading is taken.

To get the curve of Fig. 129 the field exciting current is kept constant while the speed is varied. For driving the generator for this test a variable speed motor is the most convenient. The fundamental equation shows that the electromotive force and speed curve should be a straight line, and unless the armature is driven at too high a speed the resulting experimental curve will be practically a straight line. At high speeds the short-circuited

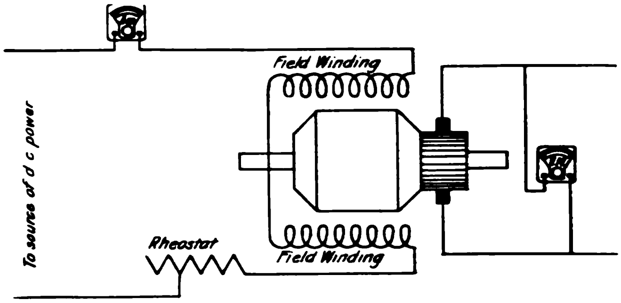


FIG. 130.

armature currents may be strong enough to react appreciably upon the flux and thus reduce the generated electromotive force.

This effect may also be present when the magnetization curve is being determined. The disturbing influence of the armature short-circuited currents can be reduced to a minimum by reducing the speed. It is preferable, therefore, to determine the magnetization curve at a speed below the operating speed of the machine, and then correct the values of the electromotive force by multiplying the observed values by the ratio of the operating speed to the speed when under test. If n is the normal speed, n' the speed under test, and E' the electromotive force corresponding to n', then E corresponding to n is $E = \frac{n}{n'} E'$.

129. Magnetization of a Shunt Generator.—The magnetization curve of a shunt generator is very similar to the magnetiza-

tion curve obtained by separate excitation. If a shunt generator is connected as shown in Fig. 131 and the field resistance varied step by step, a magnetization curve may also be obtained. This

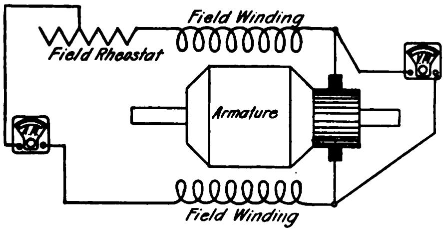


FIG. 131.

curve will not begin at the origin as already pointed out, nor will it rise to the same value for the same exciting current.

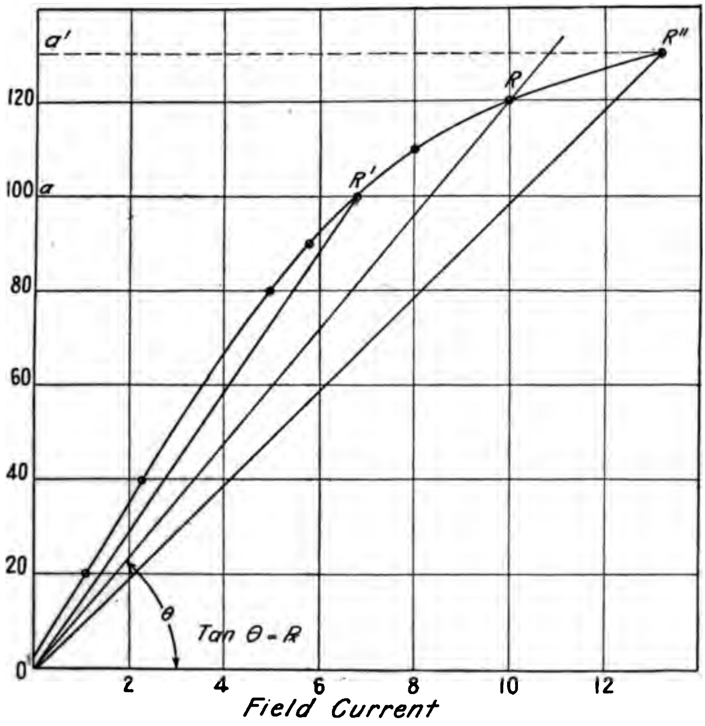


FIG. 132.

The generator whose magnetization curve is shown in Fig. 128 when shunt-excited gave the curve of Fig. 132. The two curves

are almost identical. A slight drop in voltage which is not shown is due to armature resistance. If the field current is I_f and R_a is the armature resistance, the armature voltage drop will be I_fR_a. In this particular instance $I_f = 10$ amperes and $R_a = 0.0044$ ohm; the armature drop at 120 volts would be only 0.044 volt, which is entirely too small to show in the curve.

130. Building up of the Voltage of a Shunt Generator.—A machine whose magnetic field has been previously excited will almost always retain a sufficient amount of magnetism to cause an electromotive force to be induced in the armature when running at full speed. This pressure will cause a current to flow in the field winding increasing the field flux which in turn will cause an increase in the electromotive force. The voltage and the exciting current will not, however, continue to build up indefinitely, for the magnetic flux does not increase uniformly with the exciting current, but at higher values of exciting current the magnetic circuit becomes more nearly saturated and the voltage increases at a decreasing rate.

The value to which the pressure will increase, when the armature is running at normal speed, is determined by the resistance of the shunt circuit. If from the origin we draw a line such as *OR*, Fig. 132, which makes an angle θ with the horizontal, such that $\tan \theta = R_f$, the resistance of the magnetic-field winding and rheostat, the ordinate of the point at which it cuts the magnetization curve represents the value of the electromotive force to which it will build up for this particular adjustment of the field resistance.

If the resistance is increased by cutting in more of the controlling resistance the angle θ will be increased, the field-resistance line will cut the magnetization curve at a lower point, and the final pressure to which the machine will come will be less than in the first case. This condition is shown by the line *OR'* in Fig. 132. If the field rheostat has resistance sufficient to change the field-resistance line from *OR'* to *OR''* the pressure can be varied from (*a*) to (*a'*). At (*R''*) the magnetization curve has become almost horizontal and an added field current has a very small effect in producing additional flux in the circuit.

The no-load characteristic can be determined experimentally by introducing sufficient resistance in the field circuit to vary the pressure over the total range from the value of pressure due to residual magnetism to the full value of pressure when the rheo-

stat is entirely cut out. A study of this curve shows that from the lowest pressure to that corresponding to (a') a large increase of flux is produced for a given increase in field current. From (a) to (a') the rate of increase is much less, and beyond (a') the rate of increase is almost negligible compared with the lower part of the curve.

131. Pressure Drop in Shunt Generators.—The preceding discussion considers the generator when no current is being supplied to an external circuit. Under these conditions the terminal pressure is practically equal to that generated in the armature. When a load is being supplied by the armature there is a drop in pressure. This drop is due mainly to two causes, the armature resistance and armature reactions. The drop due to the resistance of the armature is equal to I_aR_a, where I_a is armature current and R_a the armature resistance. The drop due to armature reactions has already been explained under commutation. These two causes make the terminal voltage at full load generally less than that at no load.

132. Voltage Regulation.—In order that lamps, motors, and other electrical apparatus may operate satisfactorily, in most instances constant voltage is necessary. The permissible variation in voltage from no load to full load of a generator must be small. The difference between the two values is an indication of the closeness with which the generator will maintain constant voltage. Voltage regulation is the name given to the variation of voltage with load. In order that generators of different sizes and makes may be compared with respect to this property, voltage regulation is defined as follows: *The voltage regulation is the difference between the no-load and full-load voltages expressed as a per cent. of the full-load voltage.*

Example

The no-load voltage of a generator is 135 volts. Its full-load voltage with the same adjustment of field resistance is 125 volts. What is its voltage regulation?

Solution.—

$$\text{Regulation} = \frac{E_0 - E_L}{E_L} = \left(\frac{\text{no-load voltage} - \text{full-load voltage}}{\text{full-load voltage}}\right) 100$$

$$= \frac{135 - 125}{125} \times 100$$

$$= 8 \text{ per cent.}$$

This means that the change in voltage from no load to full load is 8 per cent. of the full-load voltage.

133. Regulation Characteristic of Separately Excited Generator.—When the voltage of a separately excited generator is adjusted to a given value at no load, and the generator is loaded while the field current is maintained constant, the pressure will fall with increase in load. If a curve is plotted with the load current as abscissas and terminal voltage as ordinates, a curve

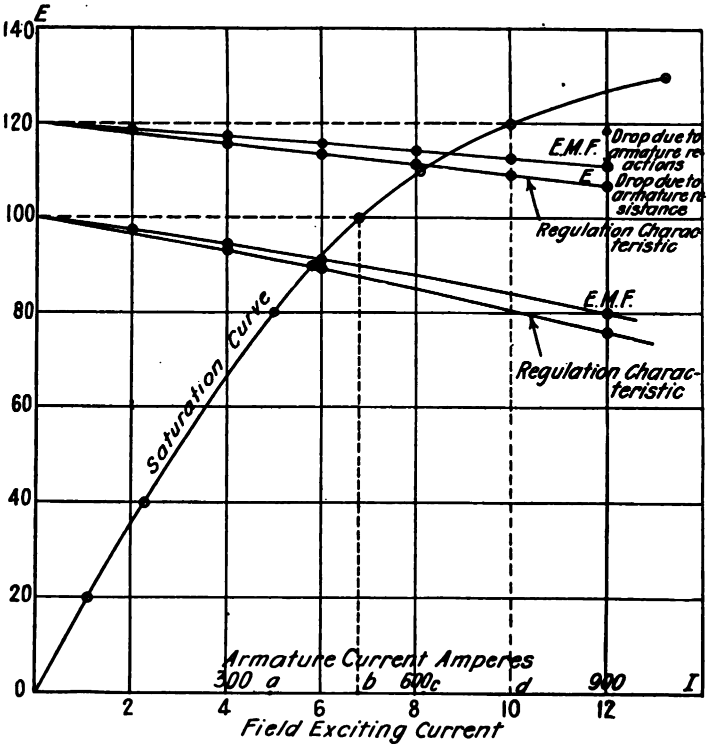


FIG. 133.

such as is shown in Fig. 133 will result. It is observed that as the armature current increases from 0 to 900 amperes the terminal voltage drops from 120 volts to 106.5 volts. This drop in voltage is due to two causes, one the resistance of the armature which in this particular generator was 0.0044 ohm, and the other the armature reaction. The part of the total drop due to each cause separately is also indicated in the diagram. It is very evident that a high armature resistance will cause poor regulation.

To obtain the regulation characteristic experimentally the generator is connected to a load which can be readily changed, and maintained constant at any desired value. A lamp bank as shown in Fig. 134 is well suited for this purpose. A voltmeter is connected across the armature terminals, and one ammeter is connected in the load circuit and one in the field circuit. The speed and exciting current are adjusted to the desired values and maintained constant while the load is increased by suitable steps. Both the armature current and the voltage are read for every change in load. The corresponding load current and terminal voltage are then plotted as shown in Fig. 133. This figure shows two regulation characteristics, one for a no-load voltage of 120 volts and the other for a no-load voltage of 100 volts at the same speed. It will be observed that the drop in voltage for the same

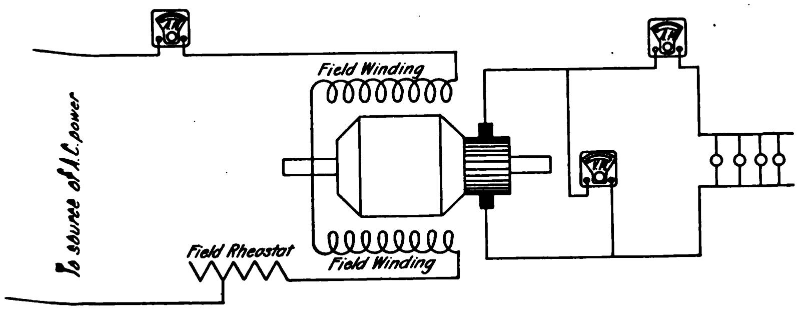


FIG. 134.

armature current is greater in the second instance. This increase in voltage drop is primarily due to the effect of armature reaction. The increased influence of armature reaction is accounted for by the fact that for a voltage of 100 volts the field excitation is below the bend of the magnetization curve and an equal change in the magnetomotive force results in a greater change of flux. Thus a change in magnetomotive force corresponding to a change in the exciting current from a to b produces a change of 20 volts, while a like change from c to d produces a change of only 10 volts.

The regulation at 120 volts no load is $\frac{120 - 107}{107} = 12.1+$ per cent. and at 100 volts no load is $\frac{100 - 76}{76} = 31.6$ per cent.

134. Regulation Characteristic of a Shunt Generator.—The drop in voltage of a generator from no load to full load when

operated as a shunt machine will be greater than when the same machine is separately excited. The two causes of voltage drop already mentioned will be present in the one case as in the other, but when the machine is operated as a shunt generator, the exciting current with a fixed adjustment of the field rheostat decreases as the terminal voltage decreases. This additional factor becomes very prominent with increasing load as is evident from Fig. 136. The drop in terminal voltage is thus due to three causes:

(a) Armature resistance.
(b) Armature reaction.
(c) Decrease of the exciting current.

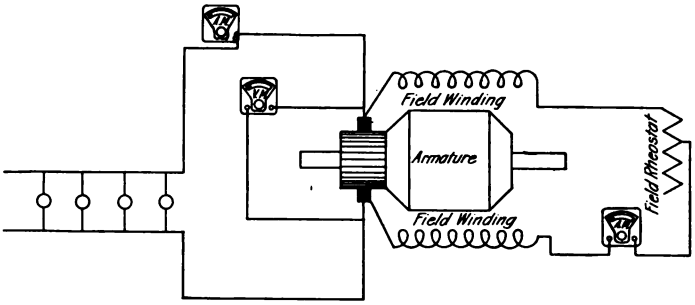


FIG. 135.

The experimental procedure to obtain the regulation characteristic is almost identical with that for the separately excited machine. The only difference is found in the connection of the field circuit which is connected in shunt with the armature, Fig. 135. The field rheostat is adjusted for normal voltage at normal speed and simultaneous readings are taken of the voltage, the load current, and of the field current. The curve is then plotted as in Fig. 136.

The explanation for the drooping of the characteristic is quite evident. As the resistance of the load circuit is decreased, the current supplied increases. The increase in current causes an I_aR_a drop and armature reaction both of which cause a decrease in the terminal voltage. With a fixed field resistance a decrease in terminal pressure is followed by a diminution in the field exciting current, which is followed by a further decrease in terminal pressure.

When the load resistance has been reduced to a value which

gives a current in this particular instance of 1000 amperes, Fig. 136, a further decrease of the load resistance is followed by a momentary increase in current, but the increased current diminishes the field flux by armature reaction causing such a drop in terminal voltage and exciting current that the load current can not be maintained. Continued decreases in load resistance will be followed by a continual drop in voltage and the load current will finally reduce to a very small value. It must not be inferred that any shunt generator may with safety be short-circuited under full voltage. In all except the smaller machines the point on the characteristic, beyond which the current does

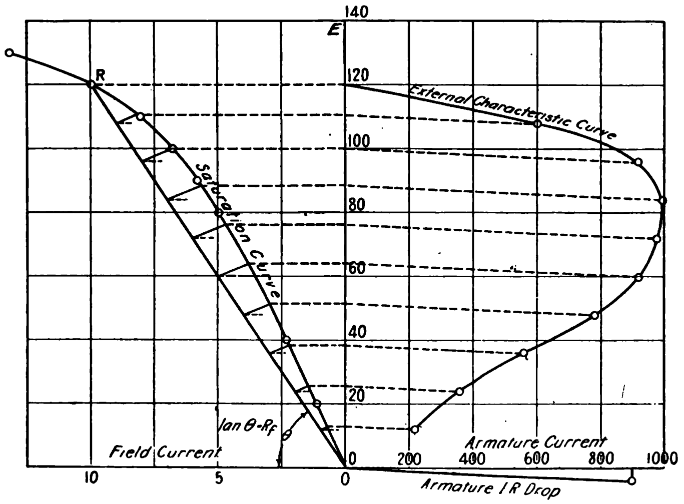


FIG. 136.

not increase, may be far beyond the current carrying capacity of the armature, and in case of a short-circuit the armature would burn out before the current decreased to a safe value.

The exact form of the regulation characteristic and the per cent. of overload current at which the critical point occurs depends on the design of the particular machine under consideration.

135. Effect of Speed upon Regulation Characteristic.—If the shunt generator be operated at a different speed, with the same adjustment of the field resistance, the regulation characteristic will be changed. If the speed is reduced, the no-load voltage will be less and as a result the exciting current will be smaller.

This will be the equivalent of operating the generator at a lower point on the magnetization curve, and a more rapid drop in terminal pressure will result. If the speed is higher, the effect will be opposite.

136. Effect of Shunt Resistance upon Regulation Characteristic.—The effect of a change in the resistance of the field circuit upon the regulation characteristic is analogous to the effect of a change in the speed, but opposite. Thus if the speed is maintained constant, and the field resistance is reduced, a larger field current will flow; this will increase the field strength and raise the voltage. The final effect will be the same as when the speed is raised. The voltages of a generator may be raised in three ways, either increase the speed, or decrease the resistance in the

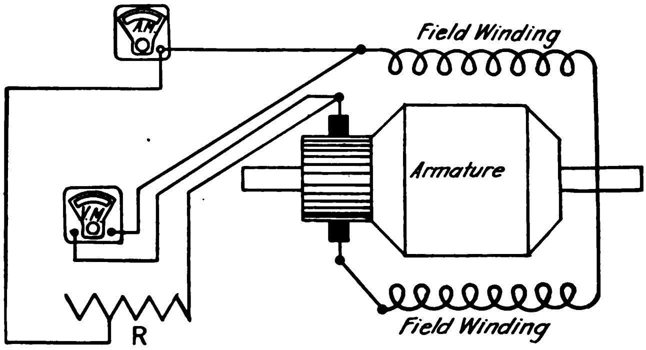


Fig. 137.

field circuit, or a combination of the two. An increase in the field resistance will have the same effect as a reduction in the speed.

137. Regulation Characteristic of Series Generator.—The connections for determining the regulation characteristic are shown in Fig. 137. When the load circuit is opened, the electromotive force induced at full speed is due to residual magnetism only. As a consequence the induced electromotive force is small. As soon as the load circuit is closed through a resistance some current will flow through the field coils exciting the field which in turn results in a higher electromotive force. A further decrease in the load resistance will be followed by a larger current and the pressure will again be increased. The relation between the load current and terminal pressure for a small series generator is shown in Fig. 138. The influence of armature

reactions and resistance becomes more pronounced as the load current increases.

Since the current usually first passes through the field circuit before it is delivered to the external circuit, the voltage indicated by the voltmeter is not exactly equal to that induced in the armature conductors. The voltage drop in armature conductors and field circuit is practically proportional to the current output. This is shown by the $I\ (R_a + R_f)$ line. This relation is not exact as the conductors and field coils increase in resistance with increase in load. The increase in resistance is not very great although in some cases it is appreciable.

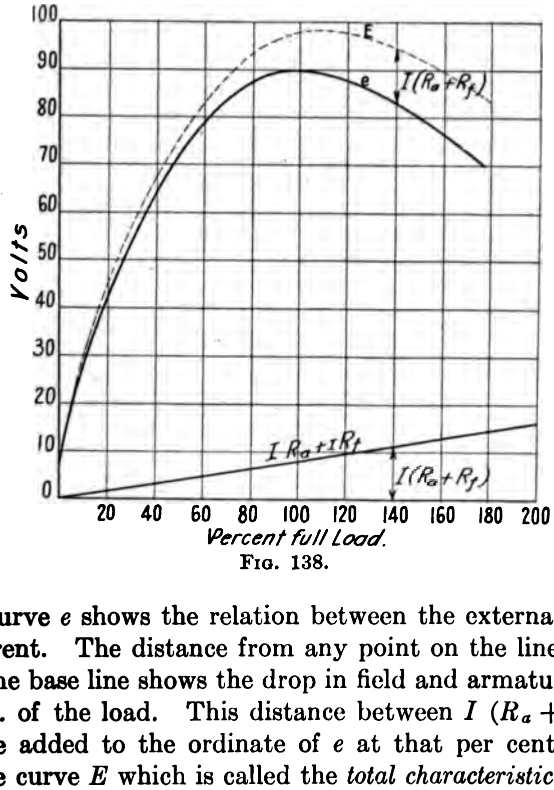


FIG. 138.

The curve e shows the relation between the external pressure and current. The distance from any point on the line $I\ (R_a + R_f)$ to the base line shows the drop in field and armature at that per cent. of the load. This distance between $I\ (R_a + R_f)$ and base line added to the ordinate of e at that per cent. of load, gives the curve E which is called the *total characteristic.*

It will be noticed that for a certain portion of the curve the increase in voltage or pressure is approximately proportional to the external or load current. Beyond 80 volts this proportionality no longer holds and the pressure drops when the current has

reached full load. Armature reactions are responsible for this deviation from the straight line. For a portion of the curve the magnetic field increases in proportion to the load current. When saturation of the field core has been reached, any increase in current does not produce a proportionate increase in the magnetic field. On the other hand, any increase in current will have a tendency to demagnetize the field, thus distorting it and causing the terminal voltage to decrease. This distortion of the magnetic field by armature current has been explained in connection with the shunt machine characteristic.

138. Effect of Armature and Field Resistance.—The armature and field resistance of a series machine should be as small as possible in order to reduce to a minimum the losses within the machine. It has been shown that the heat loss due to resistance within any circuit is proportional to I^2R. It is evident, then, that a large value of R will cause a large part of the energy of the current to be lost as heat. This will have two harmful effects: First, the energy loss will decrease the efficiency of the machine; and second, the large amount of heat will cause an excessive rise in temperature of the windings.

The series generator is slowly being displaced by other types. So long as electric lighting was performed by direct currents, the series generator was the chief, if not only, source of current for arc lighting. This was due to the fact that it was more economical to connect the arc lamps in series than in parallel. The current through one arc lamp was then the same as the current in any other lamp, or was constant. The pressure at the generator had to be great enough to force the current through the lamps and connecting wires and had to vary with the number of lamps in the circuit. Thus to supply 10 arc lamps with a current of 7 amperes requires approximately 450 volts, or 45 volts per lamp; if only 9 lamps are in the circuit 405 volts is sufficient. Hence, generators used to supply current for arc lamps are known as constant-current generators.

The characteristics of the series generator made it best suited for arc-lighting purposes. As is evident from Fig. 139, the characteristic of the series generator drops beyond 100 per cent. load. For series arc lighting the drooping external characteristic is a distinct advantage, and on this account the series-wound machine is then worked on the descending portion of the curve. For instance, suppose the generator is operating at full-load

current, 100 per cent., at a total pressure of 3000 volts; if one lamp is cut out the total resistance in the circuit is decreased and a larger current would initially result. An examination of the curve shows that an increase in the load current decreases the voltage. Although this decrease in voltage may not in itself be sufficient to bring the current back to its proper value, its effect is in the right direction. To secure the drooping characteristic the field must be highly magnetized and the armature reactions must be very prominent.

139. Regulation of a Series Generator.—As pointed out above, the regulation of a series generator is to a great extent automatic and is due to armature reactions. While the armature reactions with fixed brushes are not sufficient for efficient regulation, this system of voltage control can be made efficient by changing the position of the brushes with changes in the load. Shifting the brushes on a closed-coil armature causes an increased counter-pressure to be developed in those conductors lying between neutral and commutating planes. This reduces the pressure at the brushes the proper amount. The shifting of the brushes is accomplished by automatic electromagnetic devices.

Another method of supplementing the effect of armature reactions consists in varying the field excitation. This may be accomplished in two ways, either by varying the number of turns on the field or by connecting in parallel with the field circuit another circuit of variable resistance. The first method is not used to any extent on account of the fact that cutting in or out field turns necessarily breaks the circuit between adjacent turns and harmful sparking results. In the second method a variable rheostat is connected in parallel with the series field and the current in the field is controlled by an automatic device which operates the rheostat.

140. Effect of Speed on Regulation Characteristic of Series Generator.—For any given load current the field flux is constant and definite. Hence for a given load current the induced electromotive force is directly proportional to the speed, for electromotive force $= \dfrac{p\Phi Zn}{q \times 60 \times 10^8}$. If the characteristic for any speed n_1 is plotted, the characteristic for any other speed may readily be obtained. To do this first plot the total characteristic, corresponding to curve E, Fig. 138, then multiply the ordi-

nates of this curve by the ratio $\frac{n_2}{n_1}$ where n_2 is the new speed and from these products subtract $I(R_a + R_f)$. A curve drawn through the extremities of the ordinates will be the regulation characteristic at the new speed. Fig. 139 shows two characteristics plotted in this manner. Curves I are for a speed of 1,100 r.p.m. and curves II are for a speed of 1,300 r.p.m.

141. Effect of Shifting Brushes on Characteristic of Series Generator.—Fig. 117 shows that when the brushes of a direct-current generator are shifted the influence of the demagnetizing

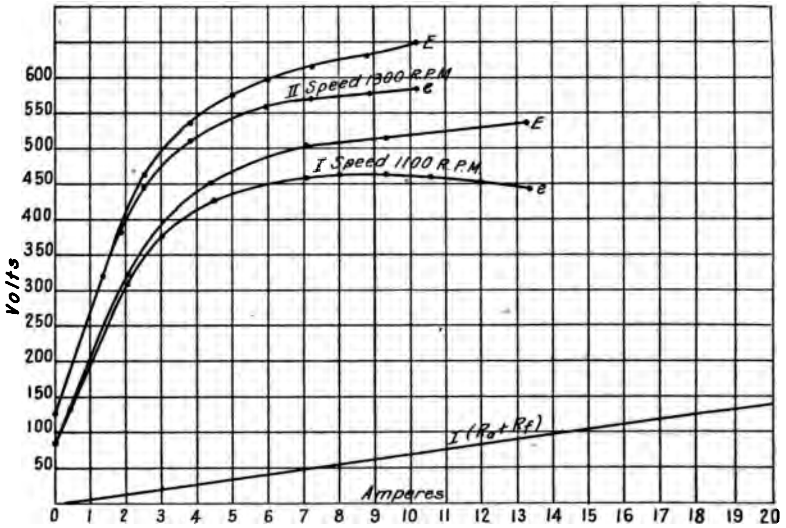


FIG. 139.

turns of the armature winding is increased. If the brushes of a series generator are shifted, the armature reactions become more influential, and cause the characteristic to droop more rapidly. If the brushes are shifted too far forward, the influence of the armature current at high loads, completely overcomes the effect of the main field and the voltage drops to zero in much the same manner as in the shunt machine.

142. Regulation Characteristic of Compound Generator.—It was pointed out that the normal shunt excitation of a shunt generator is to a point well above the bend or knee of the magnetization curve. This was also found to be true for the series generator. The point on the magnetization curve at which the

compound generator is excited will depend upon the character of the desired characteristic. The service requirements may be such that a flat or rising characteristic is desired. If the flat characteristic is desired, the effect of the compound winding must merely compensate for the voltage drop due to armature resistance and reactions. If the characteristic is to be a rising one, that is, if the terminal voltage is to increase with increase in load, the compound winding must not only compensate for the resistance and reaction drops but must provide an additional magnetomotive force. For these reasons the normal point of shunt excitation of a compound generator is somewhat below

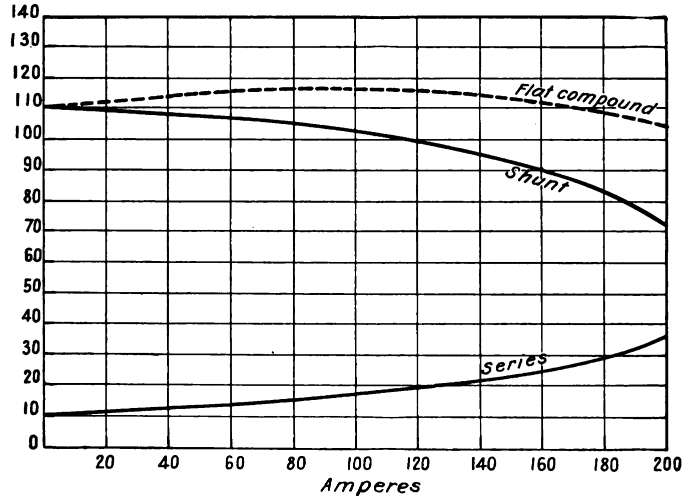


FIG. 140.

the bend of the magnetization curve. The characteristic has, then, in a measure the properties of the rising characteristic of the series generator and the drooping characteristic of the shunt generator.

143. Flat Compounding.—When it is desirable to maintain the terminal voltage at a constant value, the ampere-turns of the series field winding are adjusted so that the electromotive force is the same at full load as at no load. This is called *flat compounding*. In flat compounding the magnetomotive force of the series winding compensates for the armature reaction, and adds an additional flux the cutting of which by the armature conductors compensates for the drop due to armature resistance.

Although the compounding may be adjusted so that the terminal pressure will be the same at full load as at no load, it will not compensate exactly at intermediate loads, or at overloads. This is shown in Fig. 140. The pressures due to the series and shunt windings are shown by the lower solid lines. The combination of these produces the upper "dash" curve which is the regulation characteristic for flat compounding.

144. Overcompounding.—Where it is desirable to maintain constant or nearly constant voltage at some distance from the generator, provision must be made to compensate for voltage drop in the feeders or line. This is accomplished by adjusting

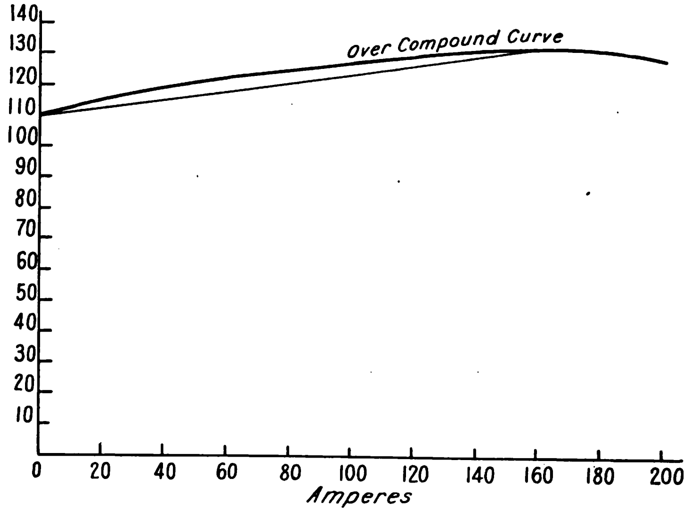


Fig. 141.

the series winding in such a manner that the regulation characteristic rises with increase in load. When such a characteristic is obtained the generator is said to be overcompounded. The characteristic of an overcompounded generator is shown in Fig. 141.

Generators used for supplying current to railway motors are very frequently overcompounded, so as to compensate for the loss of pressure in the feeder-circuits. Compound-wound generators are also largely used in lighting and power service, in order to maintain constant voltage at the motors or lamps under all conditions of load.

If the excitation of a compound generator at no load is far

above the bend of the magnetization curve, the increase in field ampere-turns with load due to the series winding can not cause a corresponding percentage increase in the magnetic flux and there will be a considerable deviation from the ideal straight-line characteristic. The regulation of a compound generator is better when the normal shunt excitation is below saturation. For flat compounding the normal shunt excitation should be higher than for overcompounding. The regulation in any case is the maximum deviation of the pressure curve from the ideal straight-line characteristic.

145. Shunt for Adjusting Compounding.—The series winding of a compound generator usually contains more turns than would be necessary if the total load current flowed through it. The proper number of series ampere-turns is then obtained by connecting a German silver shunt in parallel with the series winding. The current through the compound winding is then determined by the relative resistance of the shunt and the series winding. It is easier to secure a proper degree of compounding by an adjustment of the shunt than by changing the number of turns on the series coils.

146. Effect of Temperature upon Regulation of Compound Generator.—If the no-load shunt excitation of a compound generator is to the knee of the magnetization curve, a machine designed to give correct compounding when hot will give too high a voltage at no load. In general, as the temperature of the machine changes the relative resistance of the shunt and series windings changes. The effect of temperature upon the compounding can be corrected by inserting a variable resistance into the shunt circuit and adjusting this as the machine warms up.

147. Efficiency and Losses.[1]—Any machine is merely an instrument for the conversion and more simple application of energy, and as every such conversion necessarily wastes or dissipates some energy into unavailable or unusable forms, it follows that no machine will give out or apply to useful work as much energy as is applied to the machine. In engineering, by efficiency of a machine, is meant the energy converted and usefully applied by the machine expressed as a per cent. of the energy applied to the machine. In short, the efficiency of an electrical machine or apparatus is the ratio of its useful energy output to

[1] For a fuller treatment see LANGSDORF "Principles of Direct-current Machines."

its total energy input. Algebraically, the efficiency of a generator is usually expressed as follows:

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}.$$

For a motor, the efficiency may be calculated by

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}}.$$

The problem in design is to reduce the losses to a minimum, but as these can not be entirely eliminated no machine can have an efficiency of 100 per cent.

The losses in direct-current dynamos are due to the following causes:

(*a*) Electrical resistances of armature, brushes, brush contacts, field windings, and field rheostat.

(*b*) Hysteresis and eddy currents in the armature core and field cores.

(*c*) Mechanical friction of bearings, brushes, and air. The last is commonly called windage.

These are sometimes called copper or I^2R losses, core losses, and friction losses.

Some of the losses are approximately constant while the others vary with the load. The constant losses at constant speed are: shunt-field winding losses, hysteresis and eddy-current losses, friction of the bearings, brushes, and windage. The losses in the series field, brush contacts, and armature winding all vary with the load current.

For convenience in measurement, the total losses are sometimes classified as *copper* losses and *stray power* losses. The former class includes those that are due to current flowing through the windings of the machine. These can be obtained by measuring the resistance of the winding and the current flowing and then calculating the loss by Joule's law. The stray power losses include all the remaining losses. According to this classification the efficiency may be expressed by

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{copper losses} + \text{stray power losses}}.$$

Example

A certain 110-volt shunt generator has an armature and brush resistance of 0.06 ohm at full load of 85 amperes. The resistance of the shunt field is 45 ohms, and the stray power losses are found to be 897 watts. Calculate the full-load efficiency of the generator.

Solution.—The total armature current is the sum of the load current plus the field current.

$$\text{The field current is } \frac{110}{45} = 2.44 \text{ amperes}$$

$$I_a = 85 + 2.44 = 87.44 \text{ amperes}$$

$$I_a^2R_a = 87.44^2 \times 0.06 = 449 \text{ watts}$$

$$I_f^2R_f = 2.44^2 \times 45 = 268 \text{ watts}$$

$$\text{Total copper loss} = 717 \text{ watts}$$

$$\text{Stray power loss} = 897 \text{ watts}$$

$$\text{Total loss} = 1{,}614 \text{ watts}$$

$$\text{Total output} = 85 \times 110 = 9{,}350 \text{ watts}$$

$$\text{Total output} + \text{losses} = 9{,}350 + 1{,}614 = 10{,}964 \text{ watts}$$

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{9{,}350}{10{,}964} = 85.2 \text{ per cent.}$$

148. Variations of Efficiency with Load.—In the case of constant-speed and constant-flux machines the stray power losses

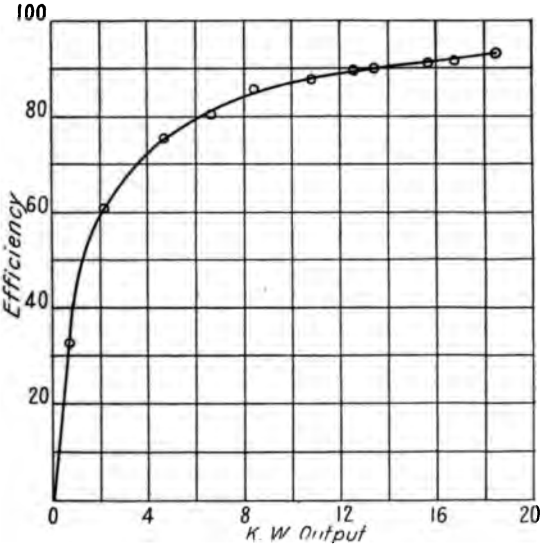


FIG. 142.

remain practically constant at all loads within the working range of the machine. In variable-speed and variable-excitation machines, as in interpole and series dynamos, the stray power loss is also variable. It is evident that the losses will be a greater per cent. of the output at partial loads than at full loads, and accordingly the efficiency of a dynamo falls off rapidly with the load. A curve showing the relation of efficiency to load of a shunt generator is shown in Fig. 142.

Recapitulation

1. The *characteristic* of a generator is a curve which shows how the physical quantities involved in its operation are related, or how when one is varied, the others vary. The three most important characteristics of generators are the *magnetization curve*, *regulation curve*, and *efficiency curve*.

2. The *magnetization curve* or *characteristic* shows how the terminal, or induced voltage, varies with the excitation at constant speed. It also shows the increase in the field flux with increase in excitation.

3. The *regulation characteristic* is a curve which shows the deviation of the voltage from a straight line with changes in load current.

4. By *efficiency* of a *dynamo* is meant the *ratio* of the useful energy output to the total energy input expressed in per cent.

The efficiencies of dynamos may be calculated by the following formulas:

$$\text{Efficiency of generator} = \frac{\text{output}}{\text{input}}$$

$$= \frac{\text{output}}{\text{output} + \text{losses}}.$$

$$\text{Efficiency of a motor} = \frac{\text{input} - \text{losses}}{\text{input}}.$$

5. Energy losses in dynamos are due to the following causes:

(*a*) Electrical resistance of armature, brushes, brush contacts, field windings, and field rheostat.

(*b*) Hysteresis and eddy currents in the armature core and field core.

(*c*) Mechanical friction of bearings, brushes, and air.

6. The *voltage regulation* of a generator is defined as the difference between the no-load and full-load voltages expressed as a per cent. of the full-load voltage.

7. The *drop in terminal voltage* with increase in load is due to three causes:

(*a*) Armature resistance.

(*b*) Armature reactions.

(*c*) Decrease in shunt field current due to decrease in terminal voltage.

The first two factors are present in all generators, and the last is found in all using shunt excitation.

8. The shape of the regulating characteristic is modified by changes in speed and excitation.

9. The *regulation* of a *generator* using shunt excitation is also affected by variations in temperature.

10. The *normal excitation for shunt and series generators* is at a point above the bend of the magnetization curve. For compound generators the normal no-load shunt excitation is at a point below the bend or knee of the magnetization curve.

11. A *flat-compounded generator* is one whose regulation characteristic is nearly parallel to the current axis. The voltage of such a generator is usually the same at no load and full load. Above full load the voltage is less and between no load and full load it is somewhat higher than at full load.

12. An *overcompounded generator* is one whose regulation characteristic rises with increase in load current. The voltage of such a generator is higher at full load than at no load.

CHAPTER XIII

OPERATION AND CARE OF GENERATORS

149. Regulating Devices.—In order that the voltage of the shunt or compound generator may be adjusted and maintained at a proper value, regulating devices are employed. For the more common uses of generators the regulating devices are of two kinds, the rheostat or variable resistance, and the Tirrill automatic regulator.

150. Field Rheostats.—Resistances for the control of the shunt exciting current, commonly called field rheostats, are made

Fig. 143.

in many forms but the general principle of operation is the same in all. The rheostat consists of some relatively high-resistance wire or ribbon of heat-resisting material and of low temperature coefficient of resistance. The rheostat is inserted in series with the shunt-field winding and is so designed that the amount of resistance in the circuit can be varied over a wide range. One form of field resistance is shown in Fig. 143. The diagram of con-

nections is shown in Fig. 144. The current from the armature enters at *a* and after passing through the resistance coils it enters the movable contact arm at *b* along which it passes to *e*, and finally by way of the connection *ed* to the shunt winding. Turning the movable arm clockwise increases or "cuts in" the resistance in circuit and thus decreases the field excitation. Turning it to the left, or counter-clockwise, decreases, or "cuts out" the resistance with a consequent increase in field excitation.

151. Automatic Regulator.—The control exercised by the field rheostat is by means of an increase or decrease in the resistance of the field circuit. This variation in the resistance may be by manual or automatic operation, usually the former. When the

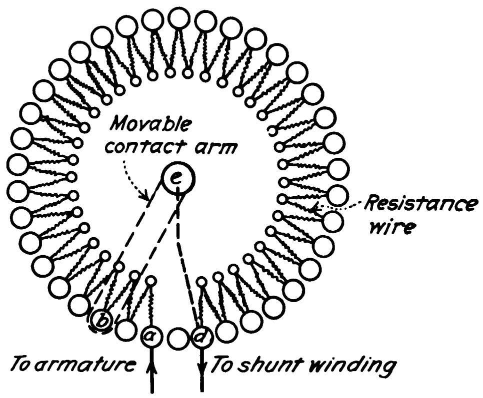


FIG. 144.

rheostat is adjusted, the resulting current is determined by Ohm's law. An automatic regulator, known as the Tirrill regulator, also changes the amount of the resistance in the field circuit, but in an entirely different manner. The resistance is not varied step by step, or uniformly, but the field rheostat is short-circuited momentarily, the duration of the short-circuit being determined by the fluctuating voltage.

When the Tirrill regulator is used, the field rheostat is adjusted so that the generator voltage is about 35 per cent. below normal with the regulator inoperative. The operation of the regulator increases the excitation to normal, where it is maintained.

The field circuit of a generator is highly inductive, and hence when the regulator operates, the exciting current does not immediately rise to a maximum value the moment the field rheo-

stat is short-circuited, nor does it immediately drop to a minimum value the moment the short-circuit for the rheostat is opened. The inductance of the field thus plays an important part in the efficient operation of the Tirrill regulator. The effect of the inductance in maintaining constant excitation is analogous to the effect of the inertia of an engine flywheel in maintaining constant speed. The Tirrill regulators are made in several different forms which are determined by the type and size of generator whose voltage the regulator is to control. The principle of operation of all forms is essentially the same.

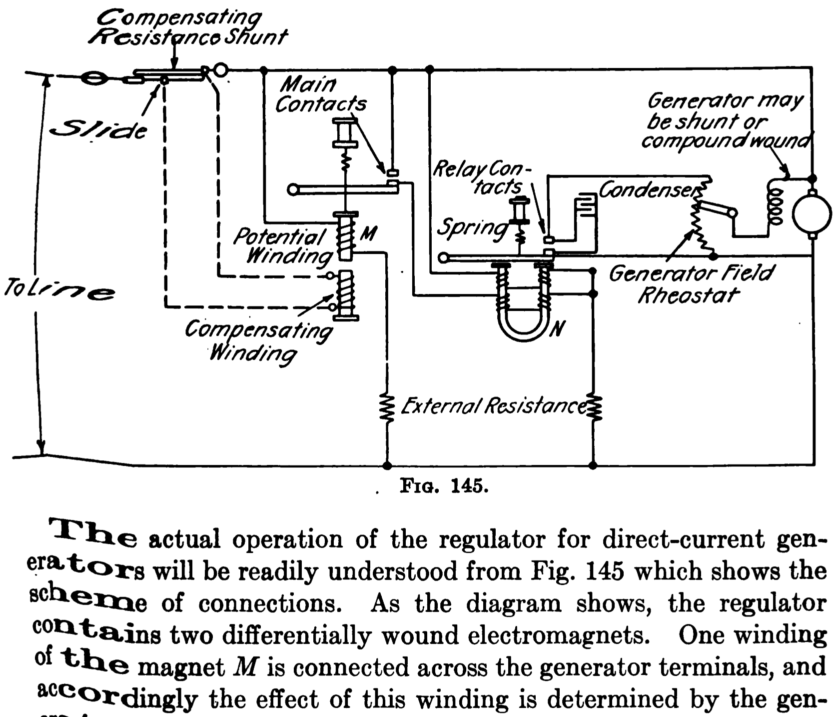


FIG. 145.

The actual operation of the regulator for direct-current generators will be readily understood from Fig. 145 which shows the scheme of connections. As the diagram shows, the regulator contains two differentially wound electromagnets. One winding of the magnet M is connected across the generator terminals, and accordingly the effect of this winding is determined by the generator voltage. The other winding of this magnet is connected across the terminals of an adjustable low resistance in series with the line. This resistance is called "compensating resistance shunt." The current through the compensating winding is determined by the voltage drop across the compensating resistance. This increases and decreases with the load current.

The electro-magnet N is also differentially wound. The upper winding is connected directly across the line and the current

through it is also proportional to the voltage at the generator terminals. The magnetic effect of this winding is to open the relay contacts whose closing short-circuits the field rheostat. The lower winding is connected to the line through the contacts which are operated by the magnet M. The magnetic effect of this lower winding opposes the action of the upper winding. If the voltage is too low, the contacts of the magnet M are closed, the pull of the spring and the opposing action of the compensating winding being stronger than the pull of the main winding. The closing

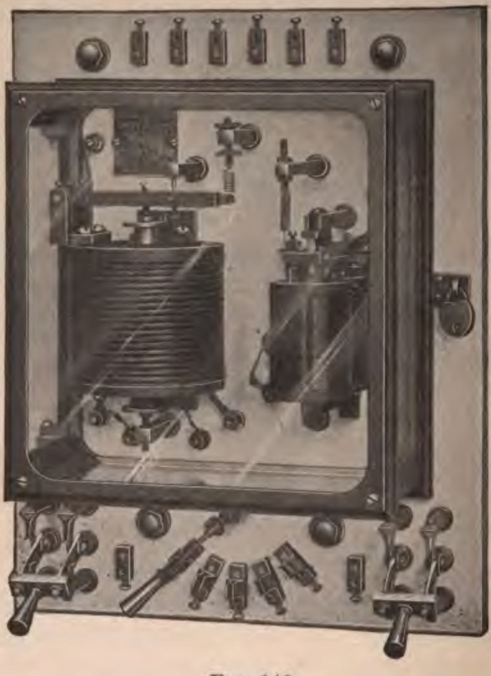


FIG. 146.

of the main contacts permits a current to flow through the lower winding of the relay magnet. The magnetic effect of this counteracts the effect of the upper winding, and the spring closes the relay magnet contacts, thus short-circuiting the field rheostat. This short-circuit is of momentary duration, for when the rheostat is short-circuited, an increased current flows through the shunt-field windings raising the voltage of the generator and causing a larger current to actuate the potential winding of magnet M. This larger current opens the main contacts, which operation is

quickly followed by a separation of the contacts of magnet *N*. The contacts thus constantly vibrate, and the excitation is maintained at the proper value. To protect the relay contact points from destruction by sparking, a condenser is connected in shunt with them.

The function of the compensating shunt is to provide a voltage drop which shall fluctuate with the load. This voltage drop sends a current through the compensating winding whose magnetic effect opposes the magnetic effect of the potential winding. As the load current increases, the neutralizing effect of the winding increases permitting the main contacts to remain closed for longer intervals, thus raising the generator voltage as the load current increases. The complete instrument designed for switchboard mounting is shown in Fig. 146. The compensating shunt

FIG. 147.

is shown in Fig. 147. The degree of compounding can be varied by sliding the movable contacts at the center of the shunt.

152. General Directions for Starting.—In handling and operating electrical machinery one principle should be followed and that is: "Be sure you are right, and then go ahead." This is a motto that should be placed in every station, and its observance would avoid many accidents. It is a good plan to do the thinking in advance and not after something has gone wrong.

Before starting any electrical machine see that the commutator and brushes are clean and the bearings oiled. The metallic dust from the commutator and brushes may cause short-circuits and should be removed with care. All switches and fuses should be in their proper places, and either opened or closed as the case may demand. If the machine is to be started for the first time, it may well be revolved a few times by hand or very slowly by power to see that it rotates freely, that the belt has the proper tension, and that it runs in the center of the pulleys. Examine

the brushes to see that the springs have the proper tension and the brushes make good contact; adjust them to the proper position by moving the rocker arm as indicated by a mark on the frame of the machine. If no mark indicates the proper position, the brushes will have to be adjusted after the machine is running and the field excited. This position of the brushes is indicated by minimum sparking, and by maximum voltage in the case of a generator, or minimum speed in the case of a motor.

The machine should be started and brought up to full speed gradually, all the switches in the case of a generator being left open. The attendant should be on the alert for trouble and in case anything goes wrong he should stop the machine instantly.

153. Directions for Starting and Stopping a Shunt or Compound Generator.—The diagrams of connections of shunt and compound generators have been shown in previous chapters. To start a generator of this type, open the main switch—if not already open—turn the hand wheel of the field rheostat so as to include all the resistance in the field circuit; start the prime mover and bring up to speed slowly, being constantly on the lookout for trouble. When the machine has reached full speed and everything is running smoothly, turn the field rheostat until the generator builds up to nearly full voltage; finally, close the main switch and adjust the voltage to the desired value. When the load consists of incandescent lamps, care must be exercised so as to prevent the voltage from becoming excessive and damaging the lamps.

To stop the generator proceed in the reverse order. First turn the hand wheel of the rheostat so as to include all of the resistance thus reducing the voltage to the lowest value; open the line switch and stop the prime mover. The main switch must be protected by fuses or circuit-breakers. In case of an overload or short-circuit the fuses or circuit-breakers will open and thus protect the generating apparatus from damage. In closing the line circuit, the circuit-breaker must always be closed in advance of the switch. First close the circuit-breaker and then the main switch. A reversal of this order may result in considerable damage should the short-circuit still exist. First closing the circuit-breaker avoids this danger, for if the short-circuit is persistent, the closing of the switch will be instantaneously followed by the opening of the breaker.

In starting a shunt generator the line switch must be left open

until the generator field cores have become magnetized. If the line switch is closed, the generator may not build up. The volt-ampere characteristic is such that, if the armature circuit is short-circuited, the voltage will drop to zero and no current will circulate in the field windings.

This is not true to the same extent of compound generators. When the main switch is closed and some load is on, a current will flow in the compound winding causing some field excitation. In some cases this excitation may not be sufficiently high to excite the field through the shunt winding. The compound generator should then be started in the same way as the shunt generator.

154. Method of Starting a Series Generator.—Since the voltage of the series generator depends upon the load current, the series generator will not build up unless the main switch is closed and some load is connected.

155. Operation of Generators in Parallel.—The efficiency of any machine is maximum when operating at full load or near full load. In any station where the load changes from hour to hour, as it will in most stations, it is advisable to have two or more similar generators which may be put into service one after the other as the load increases and be disconnected one after the other as the load decreases. Such an arrangement permits the operation of each machine at its maximum efficiency. If each machine has its own prime mover such an arrangement is especially advisable inasmuch as these may also be operated under the most economical conditions. The foregoing requirements are best fulfilled by having similar machines which may be operated in parallel. Only certain types can thus be operated.

156. Shunt Machines in Parallel.—Fig. 148 shows the connection for two shunt machines for parallel operation. The conditions for satisfactory operation are as follows:

If any machine is in operation and it is desired to "cut in" another one, the incoming machine must first be brought up to proper speed; the field must be excited so as to produce the same electromotive force at the busbars; the connections must be made so that like polarities are brought together on the same busbar or main. It is essential that these conditions be fulfilled, for if the speed has not been properly adjusted, the machine whose speed is varying will either throw its load upon the other machine or will take so much from the other as to open the cir-

cuit-breakers or blow the fuses. If the electromotive force of the incoming machine is not the same as that of the busbars, it will either take current from them and run as a motor, or supply more than its share of the current, thus becoming overloaded. When the electromotive force of the incoming machine is the same as that of the busbars, it will neither supply current to them nor take any from them when its line switch is closed. In order that the incoming machine may take its share of the load, the field rheostat is carefully cut out until the proper current is being sent over the line by the machine. Unless like terminals of the machines are connected, a short-circuit will result, the armature of the incoming machine acting as a low resistance path across the busbars.

Referring to Fig. 148, the procedure in practical operation is as follows:

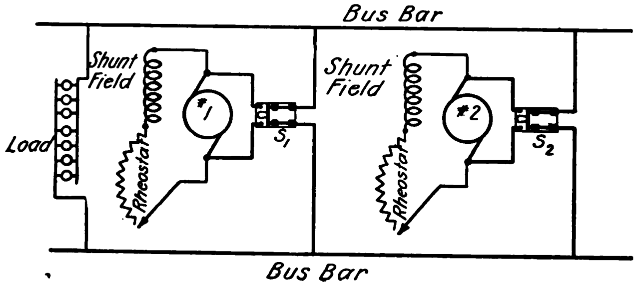


FIG. 148.

Assume that armature of machine 1 is supplying current to the lamps and it is desired to connect armature 2 in parallel with it. The switch S_1, which may be a two-pole switch, is closed when machine 1 is operating satisfactorily. Switch S_2 is open, and machine 2 is carefully brought up to speed; its field is next excited by adjusting the variable field resistance until the voltmeter indicates the proper voltage when switch S_2 is closed. Now the variable field resistance on No. 2 is further adjusted until each machine is carrying its share of the load.

To disconnect machine No. 2 from the busbars, first reduce its voltage until no current is being supplied; open switch S_2, and shut down the engine.

From the characteristic of a shunt dynamo, Fig. 136, it is evident that the electromotive force of a shunt machine falls off rapidly as the load increases. When two shunt machines are

connected in parallel, any fluctuation in electromotive force of one machine produces a like effect in the other and the operation is stable. Suppose the electromotive force of one machine to drop slightly, the other will supply more current and its voltage will also be reduced on account of the increased load. Thus, any current or voltage fluctuation in one machine automatically reacts on the other and they continue to operate with stability.

157. Operation of Compound Generators in Parallel.—Compound machines are operated in parallel in the same manner as shunt machines. On account of the fact that their characteristics are different, some changes are made in their connections. It will be seen by reference to Figs. 140 and 141 that the electromotive force of a compound generator does not decrease with the load. In the flat-compound machine the characteristic is nearly a straight line, parallel to the current axis, and in the case of the overcompound the electromotive force increases with increase in load current. Two such machines connected in parallel will be unstable in their operation. If two overcompound machines be connected in parallel without any equalizing connections, a decrease of the load on one will be followed by a drop in its voltage, which will cause a further decrease in its load and a corresponding increase in the load of the other generator. This increase in load will raise the voltage and as a result the first generator will be deprived of still more of its load. This process will continue until the current in the series field of the first machine is reversed, and the second machine is short-circuited, through the low-resistance series field and armature of the first machine.

In order to avoid this difficulty there is connected between the points A and B, Fig. 149, a wire of low resistance. This is commonly known as the "equalizer," or "equalizer connection." The function of this connection is to divide the total current furnished by the machines in the inverse ratio of the resistances of the series-field windings. When the equalizer switch is closed, it is impossible for either machine to send a current in the opposite direction through the series winding of the other, although it is possible for one machine to drive the armature of the other as a motor. The equalizing or corrective influence of the parallel connection of the series windings will become clear by a close inspection of the connections and distribution of currents. Thus, in Fig. 149, if the voltage of machine No. 1 should momentarily

fall below that of No. 2, additional excitation for No. 1 will be provided by No. 2. The equalizer connects the two series windings in parallel, and the current at B divides, part of it passing through the series coil of machine No. 2 and part along the equalizer and through series winding of No. 1. The equalizer is so connected that this auxiliary current from No. 2 raises the voltage of No. 1. If the voltage of machine No. 1 drops too low, some current from machine No. 2 may pass through the armature, driving it as a motor, but as this current does not pass in the reverse direction through the series winding there is no danger of reversing the field of machine No. 1.

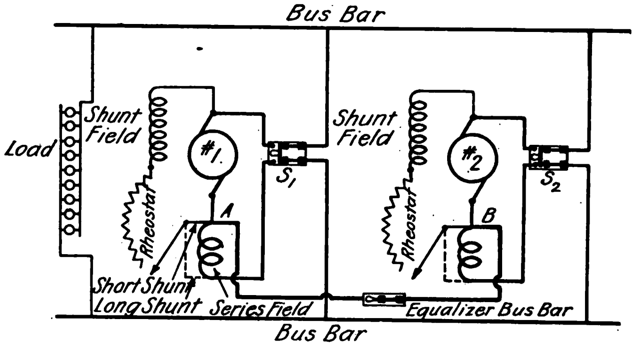


FIG. 149.

The effect of the equalizer may be studied from a slightly different viewpoint. Assume that each generator is carrying its share of the load; under this condition the voltages must be equal. The current supplied to the outside circuit divides between the series coils inversely as their resistances. It is thus evident that the resistance of the equalizer must be negligible in comparison with the resistance of either of the series windings. If this is not the case, the current will not divide properly under varying load.

158. Division of Load Between Compound Generators in Parallel.—The manner in which two compound generators will divide the load will depend upon their regulation characteristics. Flat-compounded machines will adjust themselves at different loads more accurately than overcompounded machines. When two overcompounded generators are operated in parallel and the voltage of one drops, more load will be thrown on the other machine raising its voltage. This may go on until the voltage is so high that the overloaded generator tends to drive the other one

as a motor. It is thus necessary that the regulation characteristics of the generators be the same at the busbars. If the machines have different capacities, the resistances of their series coils and leads connecting them to the busbars must be inversely as their rated load currents. This means that the fall of potential across series windings and leads will be the same under normal load.

It is very evident that a proper division of the load will depend upon the constancy of speed of the generators. If the generators

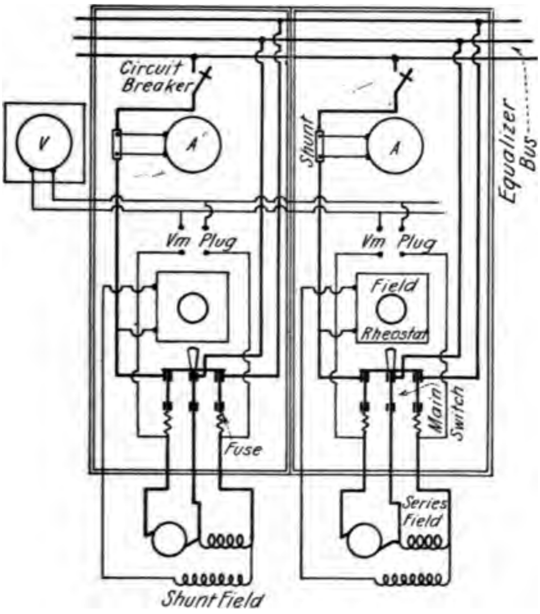


FIG. 150.

are driven by separate engines, the division of the load will be determined by the speed regulation of the engines.

The process of cutting in a compound generator differs from the process of cutting in a shunt generator very little. The difference consists in leaving the equalizer switch open until the voltage has been adjusted so that no difference of potential exists between points *A* and *B*, Fig. 149. When this has been done, the equalizer switch is closed and after that the line switch is closed. These switches can readily be combined into one three-pole switch. The equalizer switch should be made so that it will close before

the other two. A diagram of switchboard connections for paralleling two compound generators is shown in Fig. 150.

159. Operation of Interpole Generators in Parallel.—The stability of operation of two generators in parallel is determined by their regulation characteristics. If these are alike and drooping, the two machines will operate satisfactorily. The regulation of a shunt generator is inherently drooping as has already been shown.

The function of the commutating pole is to neutralize the armature magnetomotive force in the commutating zone and to provide a flux for neutralizing the electromotive force of self inductance of the coil undergoing commutation. It is thus evident that the interpole may have considerable influence upon the regulation characteristic of a generator and indirectly upon the stability of operation in parallel with another like generator.

The commutating-pole winding is connected in series with the armature in order that its magnetomotive force may vary with that of the armature winding. The increase of commutating pole flux with load current will vary in the same way as the magnetization or saturation curve of a separately excited generator, Fig. 133, that is, the flux does not increase in direct ratio with the load. The inevitable result is that while proper compensation may be secured at some load current, at a smaller load current there will be overcompensation and at greater loads the commutating pole will not supply enough flux to produce perfect commutation.

The influence of the commutating pole on the regulating characteristic of the generator may thus be considered under three heads:

(*a*) Flat or correct compensation.
(*b*) Undercompensation.
(*c*) Overcompensation.

(*a*) *Flat Compensation.*—If the brushes are properly located in the neutral or commutating plane, and flat compensation is secured, then a proper commutating flux exists for neutralizing the electromotive force of self-inductance and that due to armature reaction and no local current circulates in the short-circuited coil. As no local current flows, the terminal electromotive force will not be affected and as the armature drop and armature reaction will produce a drooping regulation characteristic, such a machine will operate satisfactorily in parallel.

(b) *Undercompensation.*—If the interpole or commutating pole does not supply sufficient flux to neutralize the voltage of self-inductance and armature reaction, the voltage that is not neutralized will send a current through the short-circuited coil in a direction, Fig. 151, such that its magnetomotive force will oppose the magnetomotive force of the field winding, and hence

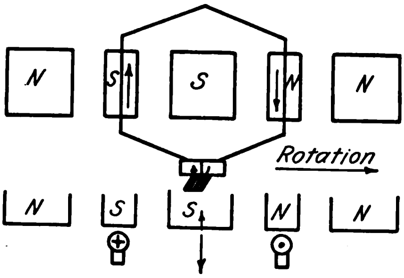


FIG. 151.

will cause a decrease in the terminal pressure, or in other words, will produce a drooping characteristic which is necessary for parallel operation.

(c) *Overcompensation.*—With the brushes in the neutral plane, and an excess of commutating pole flux, the electromotive force of self-inductance and armature reaction will be neutralized and

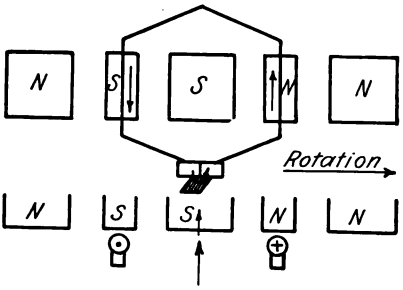


FIG. 152.

an electromotive force will be present which will cause a current to flow in a direction, Fig. 152, such that its magnetomotive force aids the magnetomotive of the field-exciting current. This will tend to increase the terminal voltages or to cause a rising characteristic which is detrimental to stable parallel operation. Whether the overcompensation is sufficient to overcome the

effects of armature reaction and armature drop will depend upon the degree of overcompensation. Usually, it will not affect the operation of the machine. The conclusion is evident that a generator with commutating poles, when correctly compensated at a certain load and with brushes in the neutral plane, will operate satisfactorily in parallel with a like machine at this and greater loads, but it may become unstable at smaller loads. If correct compensation is not present at any load within the capacity of the machine, adjustments must be made.

160. Adjustments for Proper Compensation.—If the commutating pole does not provide the proper amount of flux for compensation, two expedients may be used to correct the defect—either the ampere-turns on the pole may be increased or decreased as the case demands, or the reluctance of the magnetic circuit of the interpole may be changed by changing the length of the air gap

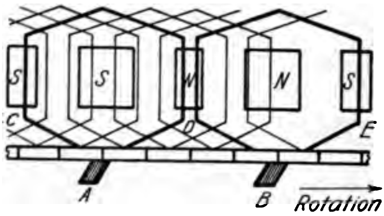


FIG. 153.

in the proper direction. The length of the air gap can usually be changed by removing or adding, as the case demands, shims between the pole and yoke. Decreasing the magnetomotive force of the interpole winding by shunting some of the turns will not give satisfactory results when the load on the generator fluctuates rapidly.

161. Effect of Position of Brushes.—The regulating characteristic of a commutating-pole generator is also influenced by the position of the brushes, as a brief analysis will show.

If the brushes are situated exactly in the neutral planes as shown in Fig. 153, the electromagnetic effect of the south interpole on the inductors between C and D is neutralized by the effect of the north interpole. The same thing is true of the other inductors, hence the total effect upon the regulation characteristic is *nil*. If the brushes are shifted backward, or against the direction of rotation, Fig. 154, it is evident that the electromagnetic effect

of the south interpole upon the inductors between C and D is greater than that of the north interpole; while between D and E the influence of the N-interpole preponderates. As the magnetomotive force of the commutating-pole winding varies with the load current, it will act as a compound winding and tend to produce a rising characteristic which is detrimental to stable

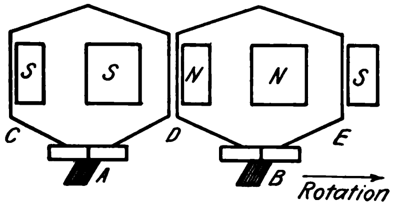


FIG. 154.

parallel operation. Analysis will show that shifting the brushes in the direction of rotation will have an opposite effect, that is, will tend to produce a drooping characteristic. This method of securing a sufficiently drooping characteristic for stable parallel operation should not be employed except in extreme cases, for shifting the brushes from the neutral planes will have an unfavorable effect upon commutation.

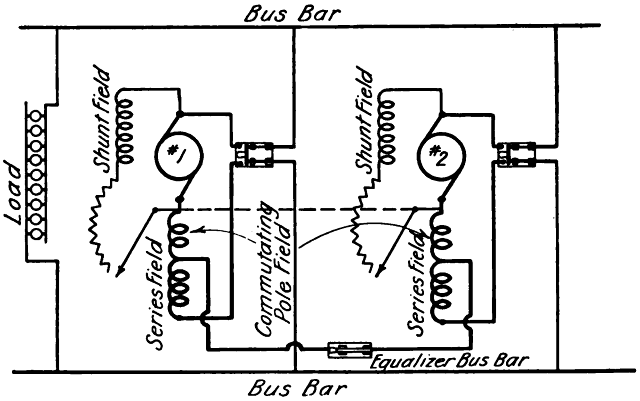


FIG. 155.

162. Equalizer Connection.—In order to secure correct compensation, the current in the winding of the commutating poles of a generator must be the same as that in the armature. Where an equalizer is employed, it should be connected between the compound and commutating pole windings as shown in Fig. 155.

163. Series Generators in Parallel.—Since the series generator has a rising regulation characteristic, two such generators can not be operated in parallel without an equalizing connection. Such generators are seldom if ever operated in parallel.

164. Dynamo Troubles.—The troubles usually encountered in operating dynamos may be classified under the following headings:

1. Failure to build up.
2. Sparking at the brushes.
3. Heating of commutator and brushes.
4. Heating of armature.
5. Heating of field magnet.
6. Heating of bearings.

165. Failure to Build Up.—Under what conditions some dynamos may fail to build up has already been briefly mentioned. A more complete analysis of the causes will now be made.

The building up of all direct-current generators depends upon the residual field magnetism. If this is absent, or if it has been reduced below a certain value, the initial electromotive force will not be strong enough to cause the generator to build up. The residual magnetism must be great enough to induce an electromotive force of sufficient strength to overcome the field-circuit resistance.

According to Ohm's law the initial exciting current depends as much upon the resistance as upon the induced electromotive force. If the field-circuit resistance is high, practically no initial current will flow. This high resistance may be due to a broken lead, poor contact of brushes, loose connection, or normally high field resistance

As already pointed out, a series generator can not build up on open circuit. On the other hand, a shunt generator will fail to build up if there is a short-circuit on the line or busbars.

The remedies to be applied, of course, consist in locating the particular trouble and correcting it. The lack of residual magnetism can readily be discovered by taking a small nail and holding it against one of the poles. If there is any residual magnetism, the nail will be held up against the pole. Never attempt this while the machine is running. A broken field connection may be discovered by disconnecting the field and attempting to send current through the windings from some outside source. A careful examination of all connections may serve to locate the trouble, if a loose contact is at fault. If the fault is due to too high a

resistance in the field circuit, an increase in the speed of the machine may generate sufficient electromotive force to overcome the difficulty. In fact in some cases the generator may be running at too low a speed, and raising the operating speed may overcome not only that, but other difficulties as well.

166. Sparking at the Brushes.—Sparking at the brushes is the symptom of either one or a combination of many troubles. Among the most common causes may be mentioned:

(*a*) Excessive current.
(*b*) Brushes not in proper position.
(*c*) Roughness or unevenness of commutator.
(*d*) Poor contact of brushes.
(*e*) An open-circuited or short-circuited armature coil.
(*f*) Armature coil grounded.

(*a*) *Excessive Current Due to Overload or Short-circuit on the Mains.*—The distortion of the magnetic field of a generator varies with the load, and hence, the position of the brushes for sparkless commutation can not be fixed. On well-designed generators no excessive sparking results with fixed brushes from no load to full load. When a heavy overload, however, comes on or a short-circuit develops, the brushes are not in a proper position and excessive sparking results.

Then again, sparkless commutation takes place only when the current density does not exceed a certain value. What this value is in any particular case depends upon the intensity of the field and inductance of the armature. It is very evident that a short-circuit or overload may increase the current density above this safe maximum. The remedy for this difficulty is self-evident.

(*b*) *Brushes not in Proper Position.*—The proper position for the brushes on generators without commutating poles is slightly ahead of the neutral point. On generators with commutating poles, the correct brush position is on the no-load neutral point. If the brushes are given a backward lead on a generator with commutating poles, the commutation will be imperfect, and the generator will overcompound for higher loads. If the brushes are given a forward lead, the commutator will likewise be imperfect, but the voltage will fall off with increase in load. When the generator is first being set up, the proper position for one set of brushes is determined for the Westinghouse machine by the aid of a templet as indicated in Fig. 156. The templet is first

fastened to the brush-holder ring. One set of brushes is then placed so that it makes contact with the templet as shown. The other sets are then uniformly spaced around the commutator. A good way to secure uniform spacing is to cut a strip of tough paper exactly equal in length to the circumference of the commutator. This strip is then divided into the same number of parts as there are sets of brushes, after which it is stretched around the commutator and the brushes set to correspond with the divisions on the paper. The templet must be removed before the armature is rotated. For other machines similar methods may be used.

FIG. 156.

To determine the position of the neutral plane the following method may be employed: First prepare two blocks of wood or fiber for each of two regular brush holders, and between each pair of blocks place a strip of copper for making electrical contact with the commutator and for connection to the voltmeter leads as shown in Fig. 157. With the machine standing, raise all brushes from the commutator and insert the two pilot brushes into two holders as shown in Fig. 158. Then excite the shunt magnetic circuit to about one-half normal value and suddenly break the circuit. If there is a deflection of the voltmeter the brushes must be shifted until no deflection is observed when the

shunt circuit is suddenly opened. When no deflection is observed the brushes are in the neutral planes. To determine the other neutral planes, change the pilot brushes to adjacent holders and proceed as before.

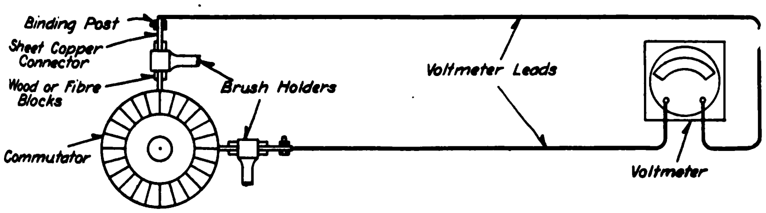


FIG. 157.

The foregoing method of locating the neutral points on the commutator is based on the principle of inducing an electromotive force by transformer action, and upon the fact that the electromotive forces induced in the armature conductors located equal

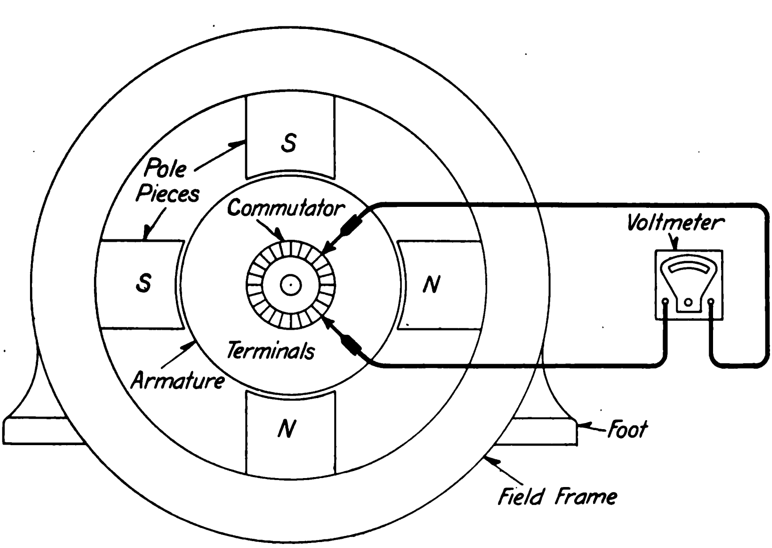


FIG. 158.

distances from the center of the pole are equal and in opposite directions. This fact will be readily understood from Fig. 159 which is a section of a six-pole drum armature. If the exciting current of such a generator be suddenly broken, the field flux will be greatly reduced in value. This sudden decrease in the

field flux induces an electromotive force in the armature conductors. It is evident from the figure that the electromotive force is in the same direction in the conductors between the brushes. This is due to the fact that all the conductors are cut in the same direction by the decaying flux. The separate electromotive forces in the conductors to the right of the central line will be added and we may assume that they will tend to send a current out at brush *B*. In the same way the separate electromotive forces in the conductors to left of the central line *CD* are also added together and they tend to send a current out at brush *A*. If there is the same number of conductors between brush *A* and the central line as there is between brush *B* and the central line,

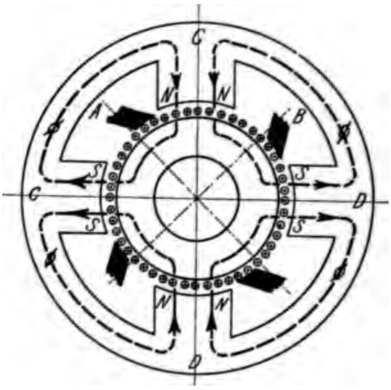


FIG. 159.

then the potential of brush *A* will be the same as the potential of brush *B* and the voltmeter will show no deflection. If the brushes are shifted in either direction from the neutral line, the potential of one brush will be higher than that of the other brush and the voltmeter will show a deflection when the shunt-field current is broken. If the armature winding is perfectly symmetrical and the commutator has a whole number of segments per pole, a position can be obtained where there will be no deflection of the voltmeter connected between two adjacent neutral points when the field current is broken; but with two circuit armature windings it is impossible to have an integral number of commutator segments per pole. When locating the neutral points on such a machine by the foregoing method, it is necessary to make a number of repeated trials. The brushes are so spaced and set

that by rotating the commutator step by step and taking readings all of the way around the sum of readings shall be a minimum, the positive and negative signs of the readings being disregarded. A check upon the correctness of the work is to space the pilot brushes from each other by an odd number of poles. If under such circumstances there is no deflection when the field current is broken, the position of the electrical neutral has been correctly established.

(c) *Roughness or Unevenness of Commutator.*—If the commutator is rough or uneven, the brush will momentarily break contact as it passes from a high to a low point. If the sparking is

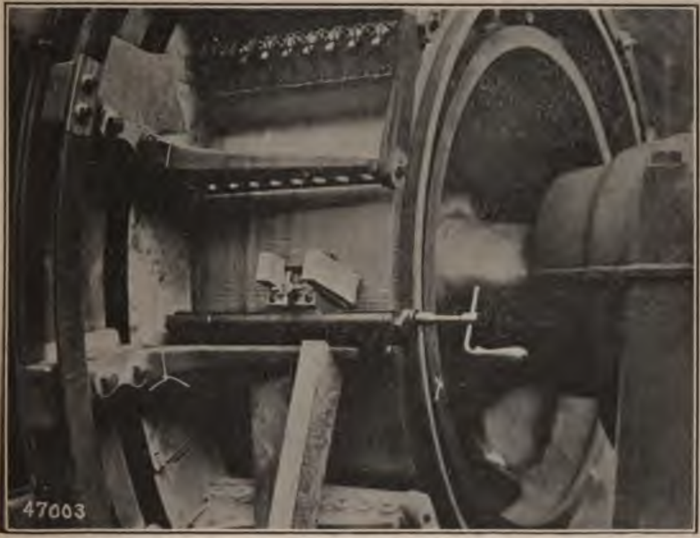


Fig. 160.

due to this cause, neglect will only increase the trouble. In fact, this is the inevitable result of sparking at the brushes no matter what the cause may be. The commuator may be eccentric, that is, not truly round. This may also cause sparking on high-speed machines. On slow-speed machines the brushes will follow the commutator.

Roughness of the commutator may be remedied by using fine sandpaper fastened in a block hollowed out to fit the commutator. If the commutator is very rough or is eccentric, it will have to be "turned." In case of small machines this is best done by removing the armature and placing it in a lathe. Com-

mutators on large machines are best turned in place. If the commutator is not too rough, a grinding device may be rigged up as shown in Fig. 160. The grinding device consists of a sandstone mounted on one of the brush-holder arms from which the brushes have been removed. The stone should be properly adjusted until a clean-cutting effect is secured. After the commutator has been "turned" in this way, it may be finished with No. 00 sandpaper. Emery cloth should never be used for smoothing the commutator.

In some instances the mica between the commutator bars may not wear at the same rate as the copper bars, or for some other cause it may become too high, causing the brush to break contact every time it passes over it. This will cause destructive sparking. The remedy for this is to cut away the mica to a depth of $\frac{1}{32}$ to $\frac{1}{16}$ inch below the adjacent copper. The practice of undercutting the mica is becoming quite general; on direct-current turbo-generators this is the common practice. Trouble is also sometimes experienced from the burning out of the mica insulation between the commutator segments. This is most likely to happen if oil or grease is used on the commutator, or if the mica becomes oil-soaked from any source whatsoever. To remedy this difficulty the mica should be carefully scraped out and the gap filled with a solution of water glass (sodium silicate) or other suitable insulating cement.

(*d*) *Poor Contact of Brushes.*—Another source of sparking is poor brush contact. If the brushes do not press evenly over their whole contact area on the commutator, there will be a greater density of current at the points of greatest pressure and sparking will result. Then again, sparking may be due to insufficient brush pressure, or oil and dirt on the commutator.

To secure uniform pressure over the whole contact area, the brushes must move freely but not loosely, in their holders, and they must conform to the curvature of the commutator. This conformity can be secured by sandpapering the brushes in a manner indicated in Fig. 161. A strip of sandpaper is slipped, with the smooth side against the commutator, under a brush and pulled back and forth. The paper must be held in contact with the commutator while it is moved.

The pressure per square inch of brush-contact area should be between 1.25 to 2.25 pounds for stationary motors and genera-

tors; 2.5 to 4 pounds for elevator and mill motors; 3 to 5 pounds for crane motors; and 4 to 7 pounds for railway motors.[1]

(e) *An Open-circuited or Short-circuited Armature Coil.*—When sparking is located at only one place on the commutator, a short-circuited or open-circuited armature coil is probably responsible for the trouble. Sometimes a loose connection manifests itself only at certain speeds.

Fig. 161.

The trouble due to loose connection, or open circuit, in the armature is indicated by a bright spark which appears to pass completely around the commutator; the pitting, however, always takes place at the segment to which the defective coil is, or should be, connected. If the trouble is due to a broken wire the defect is easily located.

[1] E. H. Martindale: *Electrical Review and Western Electrician*, vol. 70, p. 754.

1. *Testing for Open Circuits.*—To test for broken leads or connections we proceed as follows: Procure a storage battery or other source of electromotive force of low voltage and low internal resistance. Clean the commutator and substitute for one of the carbon brushes a copper strip that may be held in the hand. Connect one terminal of the battery to the carbon brush and the

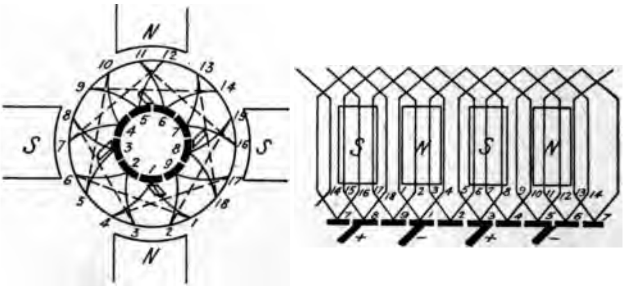


FIG. 162.

other terminal through an ammeter to the copper strip. Hold the copper brush on the commutator one or two segments from the fixed carbon brush and rotate the armature by hand. Figs. 162 and 163 show that usually there are two leads soldered to one commutator segment. If one of these is broken, the ammeter will show a decreased deflection. If both are broken, the deflec-

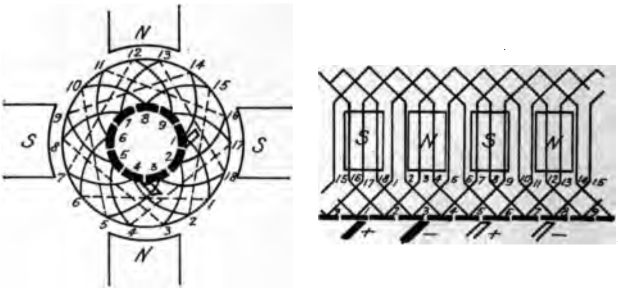


FIG. 163.

tion will be zero. That this must be true may readily be understood by reference to the figures mentioned. For instance, suppose one terminal of our battery is connected to the positive brush in Fig. 162 and the copper brush is in contact with commutator segment No. 2. If no break exists in either lead, we have two paths of low resistance in parallel and the current will be

relatively large. When one lead is broken, the current can follow only one path whose resistance will be higher and thus the deflection less. When both leads of segment 2 are broken, no deflection will result, for we then have an open circuit. The same reasoning applies in the other cases.

To locate a fault in the coil we replace both carbon brushes by metal strips and hold them against two adjacent commutator segments. An open-circuited or broken coil will be indicated by a decreased deflection, while a short-circuited coil will be disclosed by an increased deflection. An examination of the windings will show that the change in the deflection is due to the same causes as in the preceding case.

It must be remembered in making these tests that the circuit will be broken repeatedly as the brushes pass over the mica insulation between commutator bars, and these breaks must not be mistaken for faults in the armature windings.

(*f*) *Armature Coil.Grounded.*—One or more coils of the armature may be grounded; that is, electrical connection is made between the coil and the armature core. Such a ground will also produce sparking.

1. *Test for Grounds.*—A ground in an armature consists of an electrical connection between the winding and armature core. A test for a ground is best made by connecting one end of a source of electromotive force to one of the brushes of the dynamo and the other through a low-reading voltmeter to the armature shaft. A deflection of the voltmeter indicates a ground, and the ground is located near the commutator bar which gives the greatest deflection. Another method consists in sending a large, constant current from a battery or some outside source through the armature by means of the brushes. While this current is flowing connect one terminal of a low-reading voltmeter to the armature shaft and the other to one after another of the commutator segments. A deflection of the voltmeter indicates a ground which is located near the segment that gives the least deflection.

(*g*) *Weak Field.*—A weak field in many cases is also responsible for sparking. In case of a generator a low voltage will always be associated with a weak field. If the machine is a motor, the weak field will cause excessive speed. The weak field is usually due to a high resistance in the field circuit due to a faulty connection either in the field circuit or rheostat.

167. Heating of Commutator and Brushes.—This may be caused by conduction of heat from some hotter part of the machine, sparking, short-circuit between commutator segments, and imperfect electrical connection between brushes and brush holders.

Sometimes particles of copper or solder form a short-circuit or the mica insulation breaks down between commutator segments. No sparking accompanies such a short-circuit, but it is disclosed by excessive heat being developed in certain parts of the commutator. Where carbon brushes are used, it frequently happens that a poor contact between brushes and brush holders develops, and excessive heating results due to the relatively high resistance. Similarly, insufficient pressure of the brushes is accompanied by sparking and excessive heating.

168. Heating of Armature.—This may be due to the following causes:

(*a*) Conduction of heat from a hotter part of the machine.

(*b*) Short-circuit or ground in armature coils.

(*c*) Continuous overload.

An overload continued for some time causes the deterioration of the armature insulation. Continued overloading finally destroys the insulating properties of the insulating material so that the machine is incapable of carrying its normal full load without excessive sparking and heating.

169. Heating of Field Coils.—Only two or three things can cause an excessive heating of field coils:

(*a*) The heat may be conducted to the coils from hotter parts of the machine.

(*b*) Short-circuits in armature windings necessitating excessive field current for proper voltage.

(*c*) Moisture in field coils.

170. Heating of Bearings.—Bearings may become hot from any of the following causes:

(*a*) Lack of oil, grit, roughness of shaft, oil rings sticking or being displaced, too tight fit between shaft and bearing, crooked or bent shaft, poor alignment of bearings, rubbing of pulley or collar or shoulder against the bearing.

(*b*) Side thrust of armature due to uneven foundation or magnetic pull. The remedy in each case is obvious.

There are some troubles peculiar to generators and others peculiar to motors. In addition to those already discussed, the following sometimes develops in generators run in parallel.

171. Reversal of Generator.—The magnetism of a generator may be reversed when standing idle in close proximity to other machines, or by a stray current from some outside source. When the machine is next started, it will build up in the wrong direction, causing a dangerous short-circuit when connected in parallel with another generator. To obviate this danger, the shunt-field windings of all generators to be run in parallel should be connected to the busbars, for then it is not possible for one of the machines to become reversed with respect to the others.

Recapitulation

1. A *field rheostat* is a variable resistance which is connected in series with the field winding for controlling the exciting current.

2. The *Automatic or Tirrill regulator* is a combination of electromagnets and resistances which automatically control the field excitation by momentarily short-circuiting the field rheostat. The duration of the short-circuit is controlled by the load current.

3. Generators are *operated in parallel* when two or more are supplying energy to the same load circuit at the voltage of one generator.

4. The *necessary conditions* for successful parallel operation of two or more generators are:
   1. Terminals of like polarity must be connected to the same busbars.
   2. The voltages of the two machines must be the same.
   3. The generators must be of the same type.
   4. Their regulation characteristics should be alike, and inherently drooping.

5. When *compound generators* or *interpole generators* of the compound type are operated in parallel, the compound windings must be interconnected by a conductor of very low resistance. This conductor is called the equalizer.

6. *Shifting the brushes backward* on an interpole generator will tend to produce a rising regulation characteristic and hence is detrimental to stable parallel operation.

7. *Shifting the brushes forward* on an interpole generator will tend to cause a drooping characteristic and hence will increase the stability of parallel operation. A shifting of the brushes in either direction may, however, interfere with commutation, and hence, stability of operation should be secured in some other way.

8. The troubles usually encountered in operating dynamos may be classified as follows:
   1. Failure to build up.
   2. Sparking at brushes.
   3. Heating of commutator.
   4. Heating of armature.
   5. Heating of field magnets.
   6. Heating of bearings.
   7. Reversal of magnetism.

   The causes for these symptoms and their remedies will be found in the text.

CHAPTER XIV

OPERATING CHARACTERISTICS OF MOTORS

172. Service Requirements.—In the case of generators, the requirements of service determine whether a constant-current or a constant-potential generator is to be used. In the same way the great variety of service requirements determines the different designs and types of motors. Some of the applications of motors require high starting torque and rapid acceleration or increase in speed. The operation of electric railways and hoists has these characteristics. There are other applications whose service requirements are such that the motor must maintain constant speed under different loads, such as fan and blower installations. There are still others which necessitate an adjustable-speed motor, that is, the speed of the motor is to permit of adjustment to meet certain requirements at one time and different requirements at another time; many machine tools can be operated at more efficient cutting speeds if operated by an adjustable-speed motor; and finally, some applications require that the speed of the driving motor decrease, and the torque increase as the load is suddenly applied. To meet these various requirements we have *constant-speed*, *adjustable-speed*, and *variable-speed motors*.

The different speed characteristics of direct-current motors are determined by methods of excitation, and accordingly the more common classification is the same as that for generators, and we thus have series, shunt, compound, and interpole motors as well as generators. The speed and torque characteristics of these types will be taken up later. Intelligent selection of motors necessitates a knowledge of their speed and torque characteristics, together with the electrical and magnetic quantities involved.

173. Series Motor.—In this type of motor the field windings which produce the excitation are connected in a continuous path or circuit with the armature and external circuit of the machine. This form of connection is shown in Fig. 107. The electrical circuit for the series motor is the same as for the series generator, which is described in a preceding chapter.

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173. Series Motor.—In this type of motor the field windings which produce the excitation are connected in a continuous path or circuit with the armature and external circuit of the machine. This form of connection is shown in Fig. 107. The electrical circuit for the series motor is the same as for the series generator, which is described in a preceding chapter.

174. Speed-torque Characteristics of Series Motor.—Since the strength of the magnetic field is proportional to the ampere-turns on the field poles, in a series machine the strength of the magnetic field will then be proportional to the current in the armature. This is evidently true since the armature current and field current are the same.

From the torque equation $T = 7.045k\Phi I_a$ pound-feet we see that the torque is proportional to the product of the field flux Φ and the armature current I_a, and as the field flux is proportional to the armature current the torque is proportional to the square of the current. For purposes of computation, we would need to know the exact relation between Φ and I_a, but this varies considerably with the degree of saturation. The important point is the fact that the torque increased approximately as the square of the armature current, which means that the series motor will have a large torque at maximum current intake. Similarly, using the equation

$$I_a = \frac{E - k\Phi Zn}{R_a}$$

as given in Article 75, we may, by solving for n, get the expression for speed, which is

$$n = \frac{E - R_a I_a}{k\phi Z},$$

and since Φ decreases as I decreases, and increases as I increases, with constant applied voltage, or E, the speed will vary approximately inversely as I_a. R_a in the above expression is the resistance of armature and field. On account of this variation in speed with the fluctuation of the load a series motor is sometimes called a variable-speed motor. Its behavior is such that as the load decreases, the motor speeds up, and unless the motor is rigidly attached to the load the speed may become excessive and wreck the armature. The most important characteristic of the series motor is the relation between its torque and speed. Fig. 164 shows a curve which gives the relation between speed, torque, and armature current of a series motor.

It is very evident from the expression for speed, n, that for large I_a, $E - R_a I_a$ is small and, consequently, n is small. Thus at low speeds the torque is high. This property of high torque at low speeds makes the series motor suitable for starting and moving heavy loads that need to be accelerated rapidly.

For railway service it is of interest to know the pull in pounds that the motor will exert at the rim of the driving wheels at different speeds and armature currents. To give this information, tractive effort curves are plotted. Such a curve is shown in Fig. 165. It is very evident that the tractive effort curve is in form exactly like the torque curve.

175. Efficiency of Series Motors.—In Fig. 165 is also given an efficiency curve. It will be noticed that the efficiency of the motor is quite high over quite a range of load current. The maximum efficiency is reached at about 70 amperes, being about 86 per cent. at this load. Another valuable feature of the series

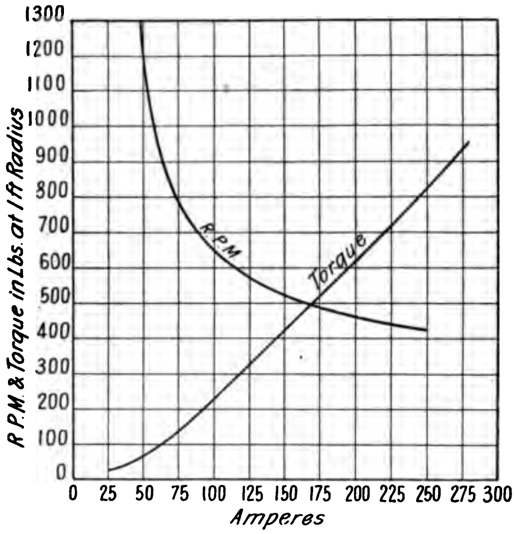

FIG. 164.

motor is the high efficiency below and above full-load current. The curve shows that this particular motor has an efficiency of over 80 per cent. at 200 amperes of load current.

The efficiency curve is for normal voltage. At lower voltages this would not be the case. The decrease in efficiency would be much more marked at overloads as the voltage falls below normal. According to definition, the efficiency of a motor is the ratio of energy output to energy input. Expressed algebraically this becomes,

$$\text{Efficiency} = \frac{\text{watts output} \times \text{time}}{\text{watts input} \times \text{time}}$$

$$= \frac{\text{watts output}}{\text{watts input}}.$$

In accordance with the above, the efficiency of a motor may be calculated when the input and output are known or can be measured.

The efficiency may also be calculated from the torque or tractive effort curves, speed, and watts input. If we represent the torque in pound-feet by T, then the work performed by the motor in one rotation of the armature is

$$W = 2\pi T \text{ foot-pounds,}$$

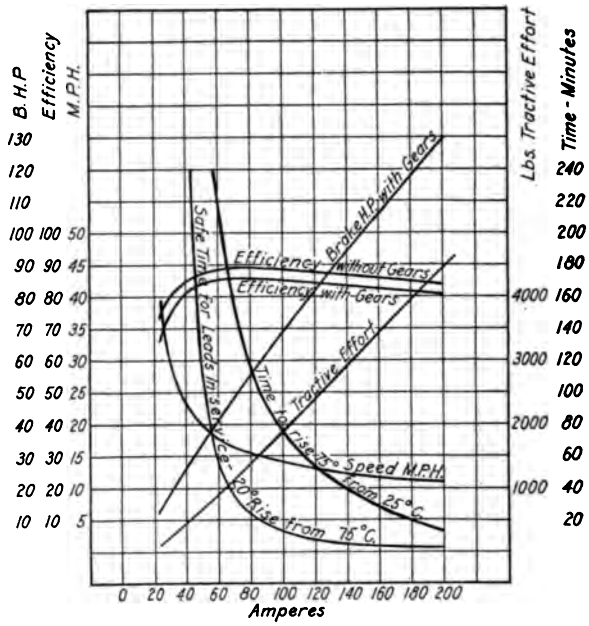

Fig. 165.

and if n is the speed in rotations per minute, then in 1 minute

$$W = 2\pi nT \text{ foot-pounds.}$$

The output in watts is equal to

$$W = \frac{2\pi nT \times 746}{33{,}000} \text{ watts}$$

$$= 0.142nT$$

$$\text{and efficiency} = \frac{0.142\, nT}{\text{watts input}}.$$

Example

What is the efficiency of the motor whose torque and speed curves are given in Fig. 164, at a speed of 540 r.p.m. and at 230 volts?

Solution.—At a speed of 540 r.p.m. the current intake is about 140 amperes. The corresponding torque is 360 pound-feet. The efficiency at this speed is, therefore,

$$\eta = \frac{0.142 \times 360 \times 540 \times 100}{140 \times 230}$$

$$= 86 \text{ per cent.}$$

The efficiency of railway motors can also be calculated from the tractive effort curve as follows:

The motor output in watts is

$$\text{Output} = \frac{\text{tractive effort} \times \text{miles per hour} \times 5{,}280 \times 746}{33{,}000 \times 60}$$

$$= 1.99 \times \text{tractive effort} \times \text{miles per hour}$$

and efficiency

$$\eta = \frac{1.99 \times \text{tractive effort} \times \text{miles per hour}}{\text{watts input}}$$

Example

Calculate the efficiency of the motor whose tractive effort curve is given in Fig. 165 at a speed of 14 miles per hour.

Solution.—At a speed of 14 miles per hour the tractive effort is 1,900 pounds. The current intake at this speed is about 100 amperes.

The output is 1.99 $\times$ 1,900 $\times$ 14 watts, and the input is 600 $\times$ 100 watts.

Hence, efficiency is

$$\eta = \frac{1.99 \times 1{,}900 \times 14}{600 \times 100} = 88.3 \text{ per cent.}$$

which checks very closely with that given in the figure for efficiency without gears.

176. Application of Series Motors.—The large torque with a relatively small current and variable speed makes the series motor specially suitable for cranes and traction purposes. When starting, the torque exerted by the motor must exceed the resisting torque due to the apparent load, in order to accelerate the masses which have to be brought up to speed. It is the ability of the series motor to provide this heavy starting torque with a comparatively small current that makes it so valuable for above-

mentioned purposes. The series motor possesses, moreover, special advantages in respect to the variation of load, which the continually changing slope of the track puts upon electric railway motors. The large torque required when running up an incline is secured with a relatively small demand on the power station.

This is only possible, of course, because of the corresponding decrease of speed mentioned above. The matter is quite clear, apart from the above consideration, if looked at from a mechanical point of view. Power is the product of force and speed. If, then, the series motor exerts a large pull with a small current, and, consequently, with a small supply of power, it is evident that its speed must be small. The load on the station will not be so irregular as with a different type of motor.

177. Speed Control of Series Motors.—As already shown, the speed of a series motor is given by $n = \frac{E - R_a I_a}{k\Phi Z}$ in which expression E is the terminal voltage applied.

178. Rheostat Control.—The above equation shows that the speed depends directly upon the applied pressure under a given value of load current. One method of speed control that at once suggests itself is by regulating the terminal pressure by means of a regulating resistance in the armature circuit. Although this method is not uncommon, there are several objections to its use. In the first place, the energy saved by running the motor at a lower speed is lost in the rheostat, and the only efficient running speed is one-half the full speed.

179. Field Control.—Another method of changing the speed is by shunting the field winding. If the field winding is shunted by a variable resistance, quite a considerable variation in the speed may be obtained. This method is, however, used to a very limited extent, as the armature reactions cause excessive sparking. The development of the interpoles, or commutating poles, has revived the use of field control for high-speed railway motors.

180. Series-parallel Control.—On street cars, speed control is secured by a combination of two methods, viz., rheostat and series and parallel connection of the motors. The essential principles of this method will be understood from an examination of the diagrammatic arrangement of Figs. 166 and 167. There is always mounted under the car a starting resistance the terminals of which are connected to the motor and to the controller on the platform of the car. When the motors are to be started

turning of the controller handle first connects the motors and resistance in series as indicated in Fig. 166. As the speed of the motors increases, the resistance is gradually cut out by a further turning of the controller handle. When the speed has reached a certain value a further movement of the handle quickly connects the armatures of the two motors in parallel at the same time inserting the resistance in series again, as shown in Fig. 167. This throws the full-line voltage across the resistance and motors. The speed then continues to rise, reducing the current intake, and as the speed increases the starting resistance is again slowly cut out until finally the armatures of the motors are subjected to the full-line voltage.

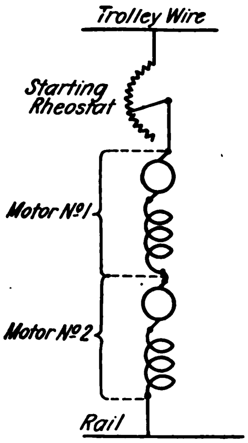

FIG. 166.

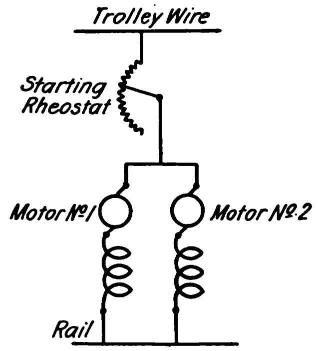

FIG. 167.

181. Shunt Motor.—The shunt motor belongs to the class known as constant-speed motors. The reason for this will appear later. The general motor equations apply equally well to the shunt motor.

182. Speed and Torque Characteristics of the Shunt Motor.—The electrical connections of a shunt motor are the same as those for a shunt generator as shown in Fig. 108. Since the field coils are connected in shunt with the armature across the mains, the field current will depend only upon the voltage between the mains, and the resistance in the shunt or field winding. The field strength will thus remain constant and the motor will maintain approximately constant speed from no load to full load. Owing to voltage drop in armature there is a slight falling off in speed from no

load to full load. The speed characteristic of the shunt motor depends entirely upon the voltage drop of the armature, the armature reactions, and the position of the brushes. The influence of the armature resistance upon the speed characteristic is evident from the equation

$$n = \frac{E - R_a I_a}{k\Phi Z}.$$

Φ is due to the shunt-field current, and, as this depends only upon the applied pressure and field winding resistance, it is constant, and hence, neglecting armature reactions, Φ is constant. In a well-designed motor the armature resistance is small and, therefore, the voltage drop $R_a I_a$ is small. Under these conditions

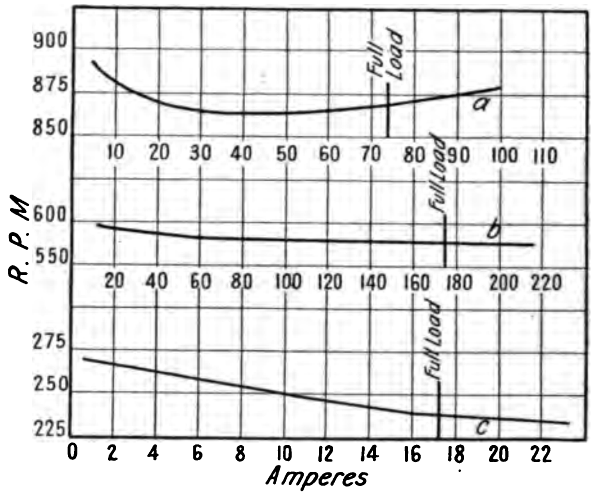

FIG. 168.

$\frac{E - R_a I_a}{k\Phi Z}$ is practically constant, and the motor has nearly constant speed from no load to full load. There are, however, some conditions which cause a variation in speed.

The armature reactions increase with load, and their effect is to weaken and distort the field. If the distorting effect is small, the effect of armature reactions is to weaken the field flux. When Φ is decreased, n, the speed, is increased as is evident from the speed equation. With the brushes fixed at the neutral point the speed characteristic is determined by the relative influences of the armature voltage drop and armature reactions.

If the former predominates at all loads, the speed will drop from no load to full load; if the latter predominates, the speed will rise with increase in load. Usually, however, the armature voltage drop has a greater effect at light loads, and at heavier loads the armature reactions predominate. The resulting characteristic drops for the first part of the curve and rises for the latter part. The relative influence of these factors is shown in Fig. 168. The speed of the motor whose speed characteristic is curve (*a*) drops off up to approximately one-half full load, while at heavier loads it rises. The speed of motors with this type of speed characteristic will be unstable when operating on the rising portion of the characteristic, and their service will be unsatisfactory.

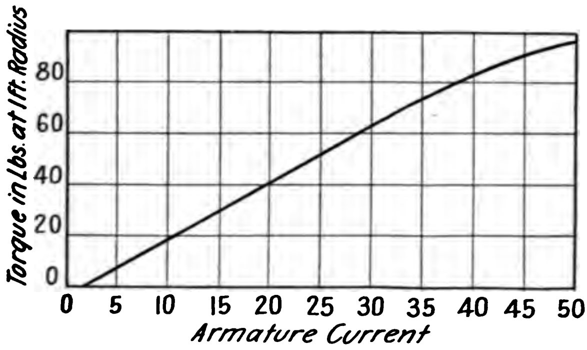

FIG. 169.

In the motor whose characteristic is shown in curve (*b*) the two effects nearly balance each other and nearly constant speed is the result.

In the motor whose speed characteristic is shown by curve (*c*) the voltage drop in the armature predominates at all loads. This is a typical characteristic for low-speed motors.

183. Torque and Armature Current Characteristic.—The torque of shunt-wound motors is proportional to the armature current as long as the field flux remains constant. This is evident from the torque equation, namely,

$$T = 7.045k\Phi I_a \text{ pound-inches.}$$

Since Φ depends upon the shunt-field current and armature reactions, it is constant until the effect of armature reactions begins to be appreciable, when the proportionality between torque and

armature current is no longer constant. The value of Φ decreases slightly until quite heavy loads are reached. A typical torque current curve is shown in Fig. 169. The curve is not exactly a straight line but is slightly concave toward the armature current axis.

184. Shunt Motor Unloaded.—When a motor runs idle, that is, without load, the torque required to maintain its speed is low and, as the torque depends upon the armature current, the armature current is small. Consequently, the loss due to the resistance of the armature winding is small and the voltage drop $R_a I_a$ is negligible.

The speed equation then becomes $n = \frac{E}{k\Phi Z}$ at zero load, but $k\Phi Z\,n$ is the counter electromotive force, so we see that at no load the shunt motor runs at a speed such as to make the counter electromotive force practically equal to the applied electromotive force.

185. The Shunt Motor Loaded.—When the shunt motor is loaded the speed must be slightly less so that the current intake may be sufficient to produce the requisite torque. The counter electromotive force will thus be somewhat less than at no load. This drop in speed from no load to full load ranges from 2 per cent. of no-load speed for large size motors to 10 per cent. or more for small motors. If the field flux were invariable the decrease in counter electromotive force necessary to permit enough current to flow through the armature could be secured only by a drop in the speed. As a matter of fact, however, any increase in the armature current decreases slightly the field flux on account of the demagnetizing action of the armature current. Consequently, the necessary decrease in the counter electromotive force is brought about partly by a decrease in the field magnetism and partly by a decrease in speed. The actual decrease in speed is less than it would be, if the field strength were invariable.

186. Application.—The shunt motor is well suited for operations requiring moderate starting torque, and constant torque at constant speed. An example of this requirement is the driving of fans and blowers of various kinds. Likewise, many of the operations in factories are of a nature for which the shunt motor is well adapted. The driving of line shafting, grinding, and buffing machines, centrifugal pumps, and numerous other kinds

of service require for satisfactory performance the characteristics of the shunt motor.

187. Dependence of Speed upon Position of Brushes.—The equation for speed shows that n varies inversely as $k\Phi Z$. If we represent the counter pressure by E_1, then $E_1 = k\Phi Zn$. Any cause affecting E_1 will affect n.

When discussing the electric generator it was pointed out that maximum voltage between the brushes is secured when the brushes are placed at the neutral points. Similarly, when the machine is operated as a motor the maximum counter electromotive force at any given speed will be induced when the brushes have zero lead. When the brushes are shifted from the neutral plane a smaller counter electromotive force is induced, and hence, a greater current flows through the armature producing greater torque, and increasing the speed. When a shunt motor is supplied from constant-pressure mains, the speed will be minimum when the brushes are in the neutral positions. Shifting the brushes in either direction will increase the speed. This method of varying speed is not feasible because it is necessary to set the brushes at the position of minimum sparking, since sparking is the most troublesome feature of these machines.

188. Speed Regulation of the Shunt Motor.—With reference to its speed characteristics discussed above, the continuous-current shunt motor is known as a constant-speed motor to distinguish it from the series motor. The change of speed from full load to no load, expressed as a percentage of full-load speed, is called the speed regulation of the motor. Thus, if the speed of a shunt motor rises from 1,500 at full load to 1,600 at no load the regulation is $6\frac{2}{3}$ per cent. The regulation is in a measure determined by the relative influence of the armature drop and armature reaction.

189. Factors Affecting Regulation.—One of the factors that injuriously affects speed regulation is a high armature resistance. That this must be so can be seen from the speed equation

$$n = \frac{E - I_aR_a}{k\Phi Z}.$$

When the load on the motor is small, I_aR_a is small and the speed is determined by $k\Phi Z$. If R_a is high, the product of I_aR_a increases with the load, and hence $E - I_aR_a$ will decrease rapidly, causing a marked decrease in n. A relatively high armature

resistance of a shunt motor may thus be the cause of poor speed regulation.

Another cause of poor regulation may be due to the condition of service rather than to the design of the motor. Thus, if the operation of a shunt motor is intermittent, the change in resistance in the field winding may cause an appreciable change in the speed. The explanation of this objectionable feature is that as the temperature of the field coil rises its resistance increases. An increase in the field resistance decreases the field current and, consequently, the field flux. This decrease in field magnetism, Φ, is followed by an increase in speed. If, then, the motor is stopped for a time, the field coils cool off with a consequent decrease in resistance. When the load is again thrown on, the same variation in speed results as the motor warms up. For operations requiring almost constant speed, such as weaving, this is very objectionable.

There are two ways of overcoming this difficulty, both of which are uneconomical. One way of improving the speed regulation of the shunt motor is to so highly saturate the field that a slight change in field current produces no appreciable change in the field flux. This method increases the power intake of the motor without increasing the corresponding output, and hence decreases its efficiency.

A second method consists in winding the field with wire whose temperature coefficient is very low. Alloys whose temperature coefficient is low have a relatively high specific resistance and accordingly wire made of any of these alloys in order to have the same current-carrying capacity and total resistance as copper, must be much larger. This means larger and more expensive field coils.

190. Speed Control of the Shunt Motor.—The constant-speed characteristics of the shunt motor make it extremely valuable for many purposes; nevertheless for some purposes, for example, for driving machine tools, it is desirable to vary the speed with the kind and character of the work. This speed control of the shunt motor is accomplished by one of five different methods:

(*a*) Armature current control.
(*b*) Field excitation control.
(*c*) Reluctance of magnetic path control.
(*d*) Multivoltage control.
(*e*) Varying voltage control.

(a) *Armature Current Control.*—One method of controlling the speed of a shunt motor is by inserting a variable resistance in the armature circuit. There are, however, some serious objections to this method of speed control. In the first place, as already pointed out under speed regulation, a relatively high resistance in the armature circuit causes very poor speed regulation on a variable load. In the second place, the expense of a separate rheostat and the extra space necessary for it may prove objectionable. The most important objection, however, is the fact that the efficiency of the system is very much reduced. The I^2R losses in the rheostat may become a very prominent part of the energy input, and the useful work of a 10-horsepower motor at quarter load may be as low as 22 per cent. of the total input.

(b) *Field Excitation Control.*—A second method of controlling the speed of a shunt motor is by varying the field excitation. This is accomplished by inserting a variable resistance rheostat into the field circuit. Any change in the field current will have a corresponding effect upon the field flux. If the motor is working under a constant load a decrease in the field strength is accompanied by an increase in speed. That is, the speed varies inversely as the field strength. A weakening of the field is momentarily followed by an increase in I_a which increases the torque with a consequent increase in speed until the counter electromotive force has reached practically its former value.

Although this method of controlling the speed is quite efficient the range of speed that can be secured in this way is small. In the first place shunt motors are usually designed to have high flux densities at normal speeds, in order that the speed regulation may be good. It is impracticable, therefore, to reduce the speed below normal by increasing the excitation current.

In the other direction, that is, increasing the speed, a somewhat greater range in speeds may be secured. If, however, the speed is weakened beyond a certain per cent., about 70, of its normal value, excessive sparking at the brushes results. The corresponding change in speed is not over 30 per cent. This, then, is about the maximum practicable range of speed control that can be secured by means of a field rheostat.

(c) *Reluctance of Magnetic Path Control.*—The field strength may, however, be changed in another way, namely, by changing the reluctance of the magnetic path. This is the method used by the Stow Electric Company on their adjustable-speed motor.

This principle is applied by making the field poles hollow and placing within each a snugly fitting cylindrical iron core. These

FIG. 170.

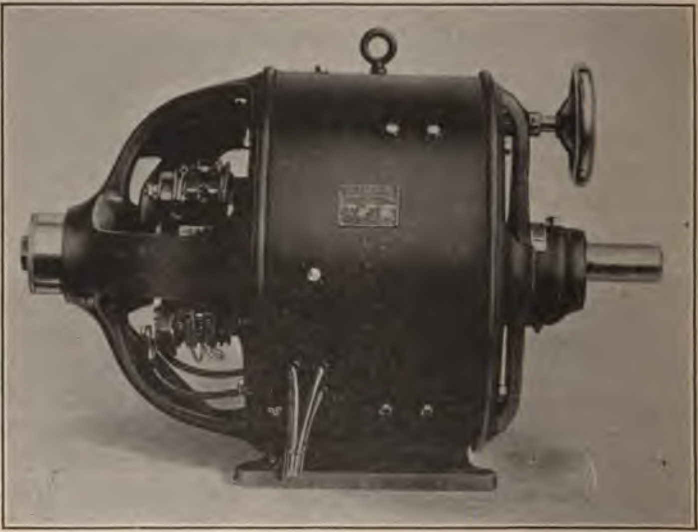

FIG. 171.

cores may be moved in or out by a system of bevel gears mounted on the frame and operated by a hand wheel. By means of thi

arrangement the width of the air gap may be increased or decreased at will. Increasing the width increases the reluctance

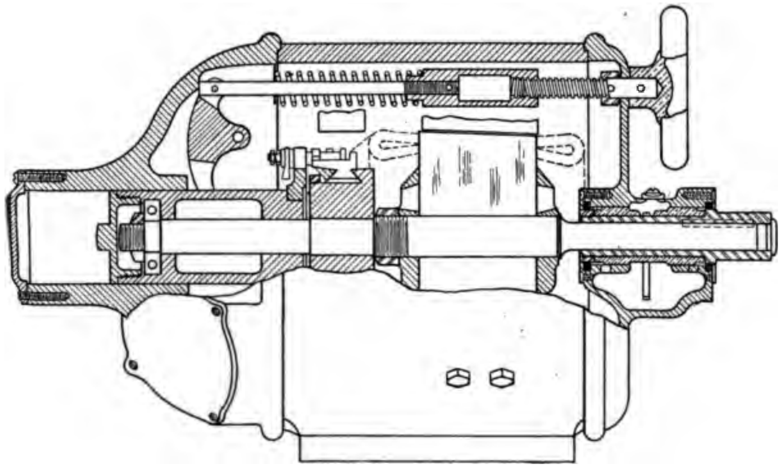

Fig. 172.

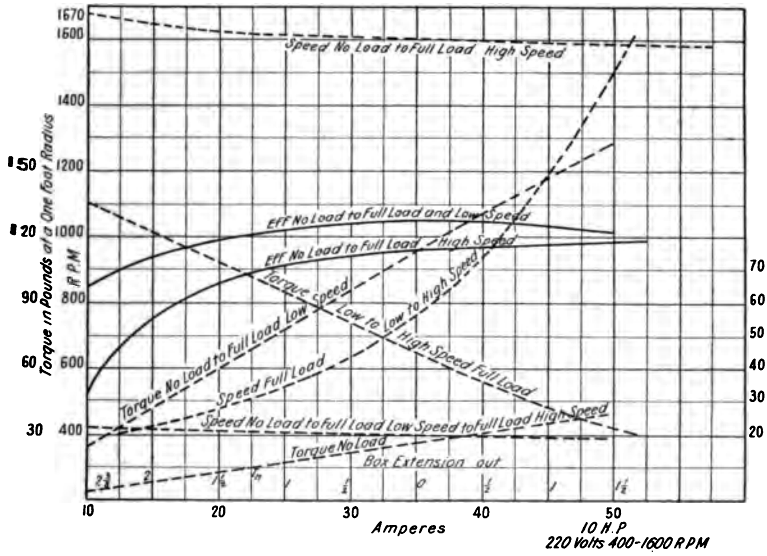

Fig. 173.

and is followed by an increase in speed. The decrease in field strength, due to an increase in the width of the air gap, obviates the troublesome sparking which usually accompanies a decrease

in the field strength by decreasing the exciting current. A motor with this form of speed control is shown in Fig. 170.

Another manner of securing the same result is employed by the Reliance Electric and Engineering Company whose motor is shown in Fig. 171. The speed adjustment is obtained by gradually shifting the armature endwise away from its normal position directly under the main field poles. The manner in which the armature is shifted will be readily understood from Fig. 172. It is claimed that ranges in speed as high as one to ten may be secured with this manner of speed adjustment. Characteristic curves of this motor are shown in Fig. 173.

(*d*) *Multivoltage Speed Control.*—It is very evident that the speed of a motor with constant excitation will depend upon the voltage applied to the armature. If, then, circuits are arranged as indicated in Fig. 174, different speeds may be obtained by

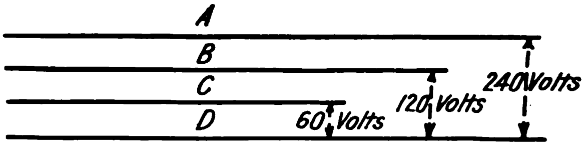

Fig. 174.

connecting the armature successively between different pairs of mains. The field winding is permanently connected between a pair of mains and then by means of a suitable controller the connections of the armature are changed for different speeds.

Such an arrangement is, strictly speaking, a multispeed device and not variable speed, since the speed of the motor is fixed when connected between a given pair of mains. A combination of this method with the one discussed under (*b*) will permit a variation of speed over a wide range. Several manufacturing companies make use of suitable modifications of this method.

(*e*) *Varying Voltage Method of Speed Control.*—To H. Ward Leonard is due the invention of perhaps the most perfect system of motor speed control. The motor which it is wished to control is provided with a separately excited field. Current is supplied to the armature from a separately excited generator. By varying the excitation of the generator the impressed voltage can be varied at will, and the torque changed to suit the circumstances. The generator is driven at constant speed, being connected to a motor which takes power from some outside source. The auxil-

iary generator supplies current for exciting the main motor, and the generator that supplies current to the armature of the main motor.

Fig. 175 shows the connections for this system. Although the connections are complicated and such an arrangement is expensive the system is used to a considerable extent for operating guns and turrets on warships.

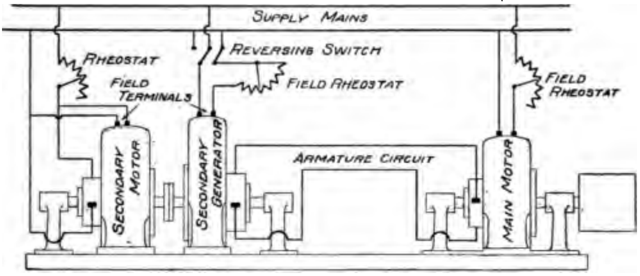

FIG. 175.

191. Efficiency of Shunt Motors.—Since the field losses and stray power losses in a shunt motor are practically constant at all loads it follows that its efficiency is very low when the load is small, inasmuch as the losses are the greater part of the motor intake. The efficiency of the motor increases as the load increases, passes through a maximum value at a certain definite load, and then with further increase of load, the efficiency decreases because of the rapid increase of armature loss. The efficiency of a motor depends also upon its size. Thus, a small motor of 1/4 horsepower may have an efficiency of about 60 per cent. while a 20 or 30-horsepower motor may have an efficiency of 90 per cent. and larger motors may have even higher efficiencies. Fig. 176 shows a typical efficiency curve.

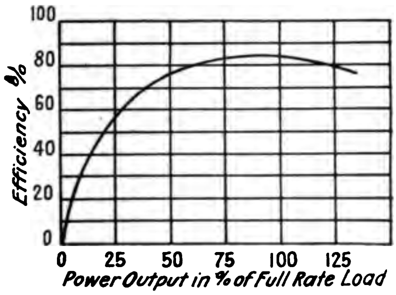

FIG. 176.

192. Compound-Wound Motors.—The field winding of a compound-wound motor may be looked upon as a combination of the windings of a series and a shunt motor. It will thus have some

of the characteristics of both. Diagrams of connections for the compound motor are given in Fig. 177.

The manner in which the compound winding is connected to the external circuit divides compound-wound motors into two classes. In one class the magnetomotive force of the compound winding reinforces the magnetomotive force of the shunt winding. When such is the case, the machine is called cumulative-compound or simply compound. In the other class the current is

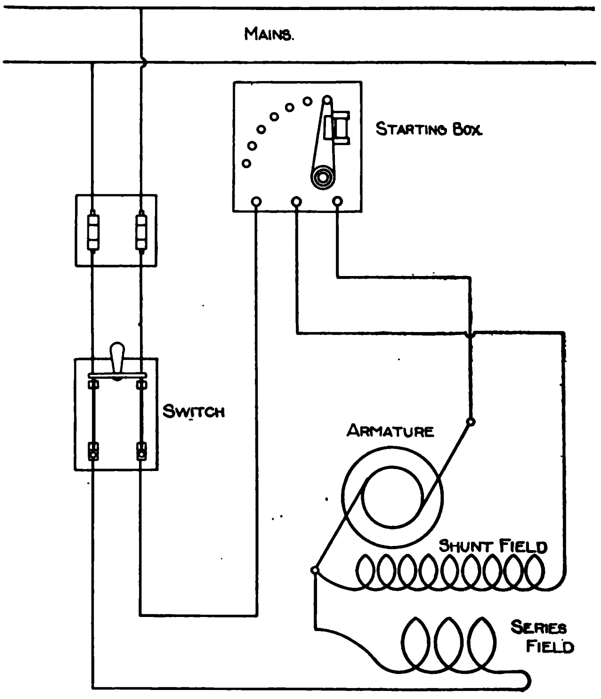

Fig. 177.

sent through the compound winding in such a direction that it tends to build up a magnetic field opposite to that of the shunt winding. Such a machine is known as a differential compound-wound motor. In ordinary commercial language motors of the first class are known as compound, while the latter are called differential motors.

193. Characteristics of Compound Motors.—In the cumulative-compound motor, on account of the magnetizing action of the series coils, the field becomes stronger with increase in load.

From the torque equation of the shunt motor we learn that the torque is proportional to the armature current as long as the magnetic flux in the field remains constant, which is approximately true in all cases from no load to full load.

In the compound motor the strength of the magnetic field increases with increase in load and the torque increases more rapidly than the armature current. That is, the torque is proportional to the product of the armature current and field flux due to both shunt and series windings. Using the notation in the previous discussion, the torque for a series motor was shown to be $T = 7.045k\Phi ZI_a$ pound-feet, but Φ varies with I_a, and,

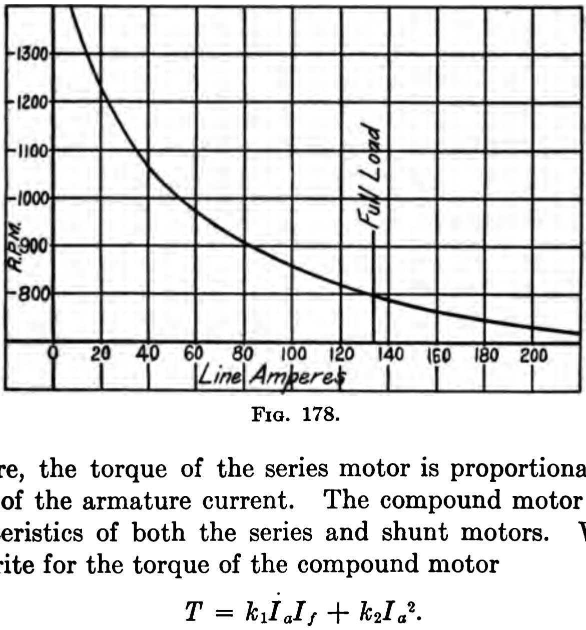

Fig. 178.

therefore, the torque of the series motor is proportional to the square of the armature current. The compound motor has the characteristics of both the series and shunt motors. We may thus write for the torque of the compound motor

$$T = k_1I_aI_f + k_2I_a^2.$$

The first term is the torque due to the shunt, and the second term that due to the compound winding.

It is very evident that as the field strength increases the speed will decrease. This decrease in speed becomes relatively less as the load increases on account of the fact that as the field strength increases the field poles approach saturation; further reduction in speed is caused solely by armature and series-field voltage drop. The speed and torque characteristics of the compound motor are determined by the relative influence of the

shunt and series windings. These two factors may be varied in any desired ratio, and the speed and torque characteristics may approach those of the series motor with just enough shunt winding to prevent the motor from running away at no loads, or they

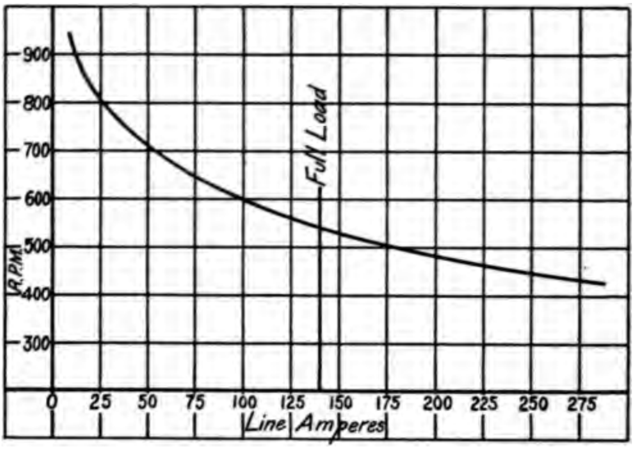

FIG. 179.

may approach the constant-speed characteristics of the shunt motor. Typical speed-current characteristics of compound motors with different degrees of compounding are shown in Figs. 178, 179, and 180. The usual practice is to adjust the shunt

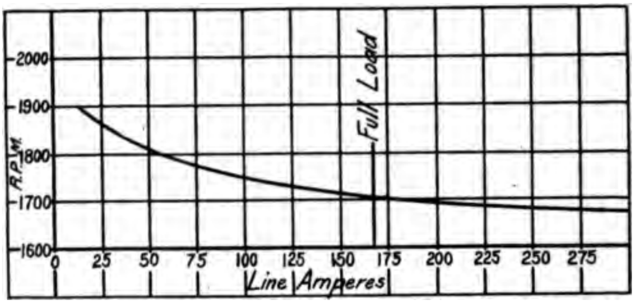

FIG. 180.

and series winding to give approximately 20 per cent. variation in speed from no load to full load.

194. Application of Compound Motors.—Compound motors with heavily excited shunt field are used under conditions requiring large starting torque and nearly constant speed. They

are employed extensively in shop practice, where a motor may be required to start under heavy load, but must maintain an approximately constant speed after starting or when the load is removed. The heavily compounded motor is employed where powerful starting torque and rapid acceleration are necessary with a speed not too widely variable under changes in load corresponding to the requirements of elevator, hoist, and similar service.

In addition to rapid acceleration a further requirement of elevator service is that constant running speed be maintained. This is secured by cutting out the series winding at full speed.

195. Speed Regulation of Compound Motors.—Since the variation in speed of the compound motor depends upon the relative magnetizing effects of the shunt and series windings, the variation in speed may be large or small. It is very evident that the speed regulation may be almost anything desired by the designer, and that it depends upon the predominance of the shunt or series characteristic.

196. Speed Control.—The methods of speed control applicable to the compound motor are those used on the shunt motor. It must be evident, however, that the shunt-field rheostat method will not give the same range of speed when used on the compound motor as when used on the shunt motor. This is especially true of the heavily compounded type. When the compound motor is used for elevator service, its speed is always controlled by a rheostat, with a final cutting out or short-circuiting of the series field.

197.—Efficiency of Compound Motors.—The shape of the efficiency curve of a compound motor depends to some extent upon the ratio of the shunt-field strength to the series-field strength. If the shunt field is much the stronger the efficiency curve will be flatter over a greater range in load than in the case of the heavily compounded motor. That is, the efficiency curve of the weakly compounded motor reaches a maximum at a small load and remains at a maximum for a large overload.

The efficiencies of compound motors are slightly higher than the efficiencies of shunt motors of the same capacities. This is especially true if the motor is carrying only a fraction of its rated load.

198. Differential-wound Motor.—In this case, the magnetomotive force of the series winding opposes the magnetomotive

force of the shunt winding, thus weakening the field with increase in load. The object of this is to compensate for the voltage drop in the armature and thus to maintain speed constant at all loads. These machines will operate satisfactorily if not overloaded, but, if an overload occurs, the field flux becomes so much reduced that the torque is not sufficient to maintain rotation, hence, the counter electromotive force falls to zero and a burn-out of the armature results, unless protected by fuses or a circuit-breaker.

In the cumulative-compound motor the starting torque is very great; this is not the case with the differential motor. The maximum series current is obtained on starting and on account of the high inductance of the shunt winding, the motor may start in the wrong direction when the circuit is closed. This is a serious objection and the series winding should be automatically short-circuited on starting. The simple shunt motor may be made to operate approximately like a differential motor by either of the following methods: by exaggerating the armature reactions by brush lag, which causes the armature current to oppose the magnetizing action of the shunt field; by an excessive number of armature turns, which also causes the demagnetizing action of the armature current to be excessive; and by a proper use of interpoles.

The ordinary shunt motor has many advantages over the differential motor, so the latter is little used.

199. Interpole or Commutating Pole Motor.—To meet the demand for an adjustable-speed motor, there has been developed a type of motor akin to the compound motor but having a wider range of speed variation. As has been shown, the field winding of the compound motor consists of series and shunt windings both placed upon the same field cores. The interpole motor, as its name indicates, differs from the compound motor in having the series coils upon cores midway between the regular poles.

200. Operating Characteristics of Interpole Motors.—In discussing armature reactions, it was pointed out that the field flux, in the shunt motor, is more and more distorted as the load increases. On account of this distortion, the shunt motor can carry only moderate overloads without excessive sparking.

The function of the interpoles is to provide a commutating flux so as to prevent this excessive sparking during overloads, and change in field strength. The manner in which this is accomplished is by placing small poles midway between the regular

poles, Fig. 181. These interpoles are much thinner than the main poles and are wound with coils connected in series with the armature. This winding is connected so that the interpole has the same polarity as the main pole immediately back of it with reference to the direction of rotation. Thus the armature coil first passes under the main pole and then under the interpole of like polarity. As the load increases the main field is weakened but that due to the interpole increases. As the brushes are placed so as to commutate the current in the coils when under the interpoles, the increase in the field under interpoles provides sufficient flux to permit commutation without sparking. In some

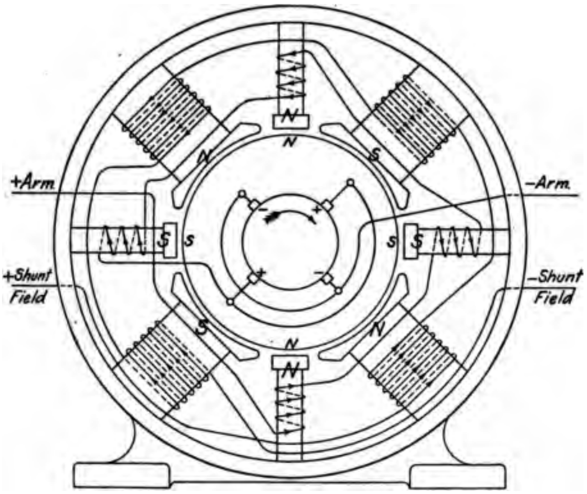

FIG. 181.

cases the interpole winding is shunted so that only a portion of the armature current produces the auxiliary field. When this is done the shunt is adjusted so that the additional field prevents sparking for large overloads, and for large variations in speed. Shunting the commutating pole windings on motors is objectionable for the same reason as on generators. The operating characteristics of the interpole motor are to a great extent determined by the degree of compensation secured by the interpole winding, the magnetic saturation of the interpole, and the position of the brushes.

When the commutating pole winding just neutralizes the reactance voltage in the coil undergoing commutation, no short-

circuited current flows in the coil. If the commutating pole winding overcompensates the short-circuited voltage, a current flows in the coil in such a direction as to demagnetize the main field, and *vice versa.*

If the commutating poles are saturated when the motor is carrying only a small per cent. of full load, the effect will be the same as if it were wound with too few turns, that is, it will be undercompensated at full and overloads.

A shifting of the brushes in either direction will produce a cumulative or differential compound effect. If the brushes are shifted against the direction of rotation, the counter electromotive force is reduced; at constant applied electromotive force the armature current increases, which strengthens the magnetism of the interpole and the counter electromotive force is still further reduced. This action will continue until the interpole becomes saturated when the higher speed, which accompanies the increase in armature current, increases the counter electromotive force at a higher rate than it is reduced by the effect of the increase in magnetism of the interpole. If the inertia of the motor armature is great, the speed may increase to such an extent that the counter electromotive force is momentarily higher than the applied electromotive force. This will be followed by a drop in speed below normal, and the operation of the motor will be unstable. If the speed drops too low, the armature current may become momentarily excessive and short-circuit phenomena may take place. If the brushes are shifted in the direction of rotation the result is to increase the counter electromotive force and lower the speed for the same load.

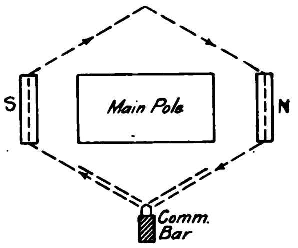

FIG. 182.

In order to understand the influence of the degree of compensation effected by the interpoles and their saturation upon the speed characteristic let us consider the action of the short-circuited current in the coil undergoing commutation. Fig. 182 shows the relative position of an armature coil undergoing commutation with reference to the main pole and commutating poles. If any current, no matter what its source, is flowing in this coil its magnetomotive force must either assist or oppose the magnetomotive force of the main field winding. When the

commutating pole is overcompensated a current flows in such a direction as to demagnetize the main field. Slight overcompensation is beneficial in reducing sparking, but excessive overcompensation, especially on machines working with a weak main field, such as adjustable-speed shunt motors at higher speeds, has the same effect as a differential winding. The effect of overcompensation on the speed current characteristic is disclosed in curve (*a*), Fig. 183. The speed increases with increase in armature current until the motor takes about 50 amperes, which is about one-half load for this particular motor. Beyond this point the speed rapidly decreases or the characteristic is that of an under-

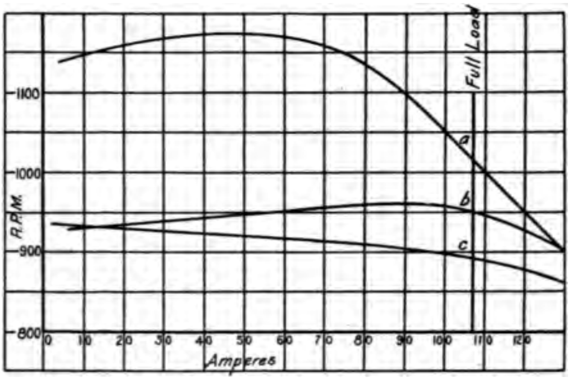

FIG. 183.

compensated motor. This effect is due to the saturation of the interpoles. Reducing the ampere-turns on the interpoles, or increasing the size of the interpoles, is followed by a more uniform speed as is shown by curve (*b*). A further reduction of ampere-turns, or an increase in the reluctance of the interpole magnetic circuit, gives the drooping characteristic shown in curve (*c*).

When the load is suddenly thrown on an overcompensated interpole motor it is liable to hunt, that is, its speed will alternately increase and decrease. Whether the sudden fluctuations will die out in time or whether they will increase in intensity will depend upon the conditions of the magnetic and electric circuits, inertia of motor armature, and character of load. All motors with rising speed-current characteristics are likely to be unstable in operation, and for this reason motors whose speed is adjust-

able by varying the field excitation should have a drooping speed characteristic at high speed between no load and about 50 per cent. overload.

201. Efficiency of Interpole Motors.—The efficiency of the interpole motor at full load is of about the same order as that of motors of other designs. At low speeds and partial loads its efficiency is somewhat higher. This is disclosed by the curves of Fig. 184.

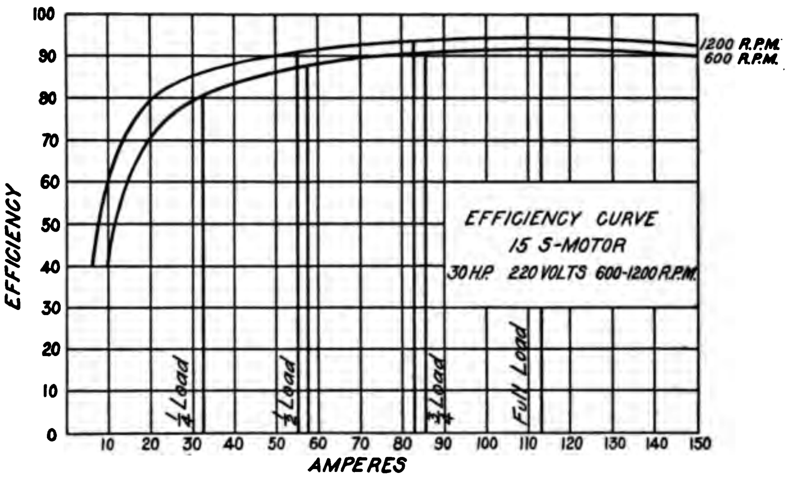

FIG. 184.

202. Speed Control of Interpole Motors.—Since the interpoles provide a commutating field which prevents sparking while the main field changes greatly, it is evident that the best method of changing the speed of the interpole motor is by means of a field rheostat. For this purpose any suitable rheostat may be used, but it has become the practice to provide special rheostats for starting and controlling the speed. These rheostats differ from the ordinary shunt-motor starting rheostat in that the shunt-field resistance is never cut out. When the lever is moved over to the running position all of the resistance in series with the armature is cut out, but the lever may be moved back, increasing the resistance in series with the shunt winding. This weakens the main magnetic field and the speed increases accordingly.

203. Application of Interpole Motors.—The use of interpoles has considerably extended the field of the direct-current motor.

This extension has taken place mainly along two lines. In the first place, the motor may be used for operating machinery, the efficient production of which depends upon the possibility of changing speed. In the second place, higher voltages may be used with a corresponding saving in line wire and weight of motor. Before the development of the interpole motor the practical limit set for railway motors was about 600 volts. The improvement in commutation secured by the introduction of interpoles permits the use of pressures as high as 1,200 volts. This means that either the transmission lines may be made smaller, or that the range of distribution may be increased.

204. Motor Controllers.—As the service requirements of motors are numerous, numerous devices have been designed and constructed for starting, stopping, changing the speed, and in other ways controlling the motor. Only the simpler apparatus and methods employed will be discussed here. A more complete treatment can be found in technical journals.[1]

205. Starting and Stopping Motors.—Since the current any motor will take is mainly determined by the counter electromotive force, and on starting there is no counter electromotive force, means must be provided for controlling the starting current. In direct-current machines this is usually done by means of a starting rheostat. In large motors it may be done by controlling or regulating the supply voltage. Fig. 185 is a diagram of the wiring of the usual type of a series motor starter with no-load release, M, in series with the motor armature. The motor is started by first closing the line switch after which the armature circuit is closed by moving the rheostat arm A to the right. As soon as this arm makes contact with button 1, the current can flow through the armature and series field winding and the motor should start. If it does not start, the arm is moved over to the second or if necessary to the third button. If the motor does not start when the third button is reached, the arm should be returned to the starting position, the line switch should be opened and an open circuit, overload, or other cause of trouble investigated.

On starting, the armature current is mainly determined by the rheostat resistance R, and the counter electromotive force of the motor. If the rheostat arm is moved too slowly this resistance may become damaged, but if it is moved too rapidly

[1] *Electric Journal*, vol. 11, pp. 656 *et seq.*

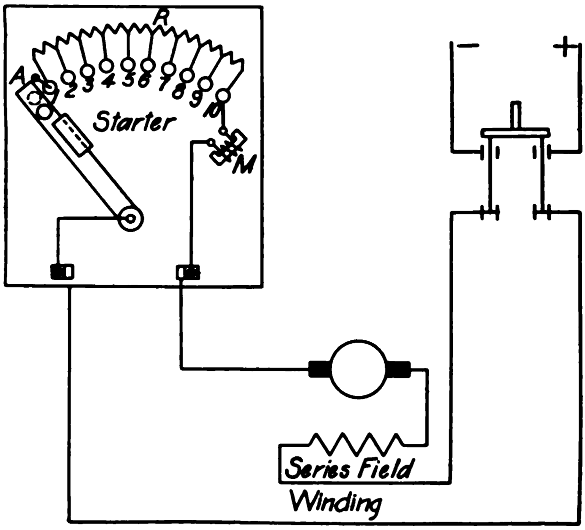

FIG. 185.

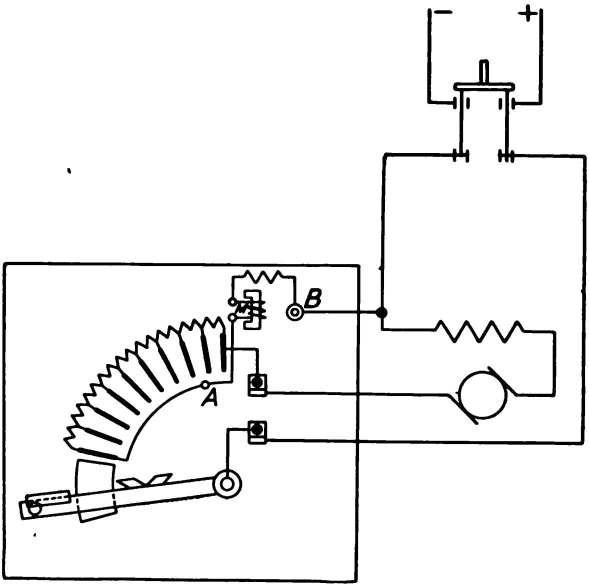

FIG. 186.

the motor may not accelerate quickly enough to develop sufficient counter electromotive force to keep the current within the working range, and the motor may be damaged. The speed with which the arm is to be moved will depend upon the size of the motor and the character of the load.

When the rheostat arm has been moved to the extreme right it is held in place by the electromagnet, *M*. If the circuit is opened at any point, the electromagnet is demagnetized and the arm is returned to the starting position by a spiral spring on the hub of the arm.

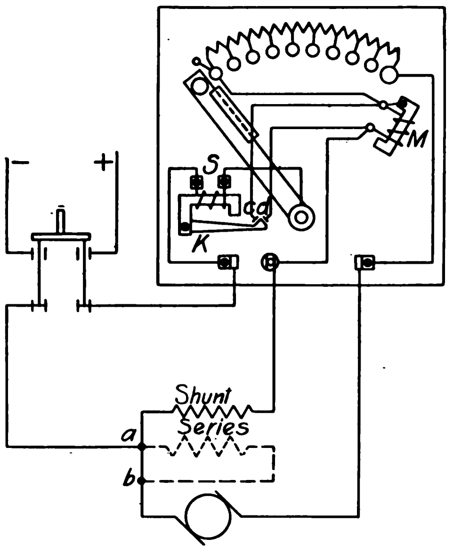

Fig. 187.

In the diagram of Fig. 185 the electromagnet is connected in series with the armature and accordingly its excitation varies with the load. A better way is to connect the no-voltage release, as the electromagnet is called, across the line. A diagram of the connections for a rheostat with such a connection is shown in Fig. 186. For shunt and compound motors the starters are of much the same design. On account of the shunt-field winding the connections are slightly different. Fig. 187 shows the connections for a typical shunt, or compound motor starter. This is provided with two electromagnets; one, *M*, in series with the shunt-field winding and the other, *S*, in series with the armature.

The latter is known as the overload release. In case the armature current becomes excessive the electromagnet S attracts the armature K which as it moves upward short-circuits the winding of electromagnet M at points c and d. As soon as this occurs the rheostat arm is released and returns to the starting position. The manipulation of such a starter is exactly the same as of that shown in Fig. 184. Sometimes shunt motor starters are made with four points of connection instead of three. A connection diagram of such a starter is shown in Fig. 188.

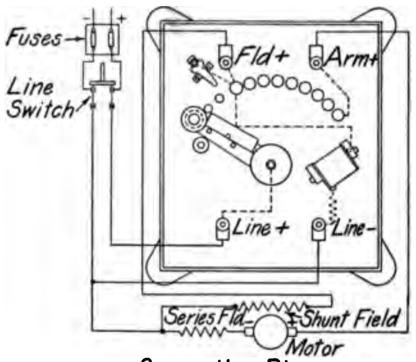

FIG. 188.

206. Speed Controllers or Regulators.—The general principles of speed control of motors have been given. The resistance speed regulator may be described as a starting rheostat with sufficient resistance to carry the full-load current continuously on any step. The speed regulation of shunt-wound and compound-wound motors may be effected in two ways: by inserting resistance in the armature circuit of the motor; or by inserting resistance in the shunt-field circuit. The limitations of these methods have already been pointed out. A diagram of connections for a series controller is shown in Fig. 189. The rheostat resistance is in series with the motor armature. The no-load release holds the arm in any position it may be left by means of a dog which fits into the notches corresponding to the contact points on the rheostat. This arrangement makes it impossible to stop the arm anywhere except on the center of the contact, and whenever

the voltage drops below a certain value the regulator arm is released and returned to the off position.

A controller employing both armature and shunt resistances is shown in Fig. 190. As is evident from the diagram, when the rheostat arm is moved to the first contact point, there is no resistance in the field circuit other than that of the winding itself. The resistance R, however, is all in series with the armature circuit. When the arm is moved to contact point 8 all of this resistance is cut out of the armature. A further movement to the right of the arm inserts some of the resistance f into the field

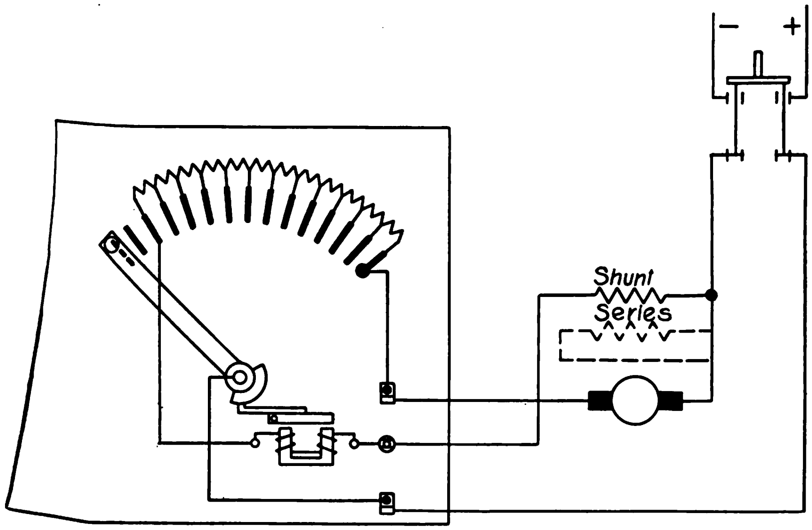

FIG. 189.

circuit. Speeds below normal are obtained by the motion of the arm from contact 1 to contact 8, and speeds above normal are obtained by moving the arm along the contacts from 1′ to 14. The diagram also shows a no-voltage and overload release.

Connections for a combination starter and speed regulator are shown in Fig. 191. In starting, the two arms A_1 and A_2 are moved together toward the right as in the ordinary or simple starter. When the arm A_1 comes into contact with electromagnet M it is held in place, but A_2 can be moved to the left which movement inserts the upper resistance into the field circuit. The field circuit is permanently joined to one end of the field

resistor at *b*. Current entering at this point has two paths: one through the field resistor and the arm A_2, and the other through the switch *a*, the armature resistor, and the arm A_1. At starting, the resistance of the latter path is much smaller than that of the former, and at the end it is much greater. When the lever A_1 is moved to its running position, the switch *a* is opened and the field current must pass through the field resistor only. To increase the speed of the motor the arm A_2 is moved to the left.

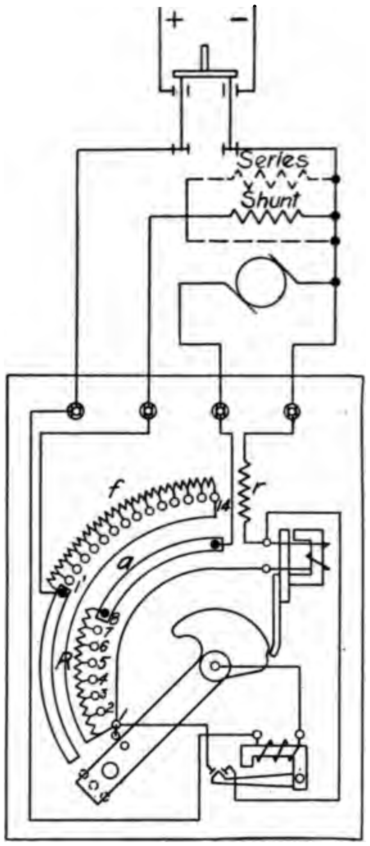

FIG. 190.

To reverse the direction of rotation of a direct-current motor it is necessary to reverse the connections of either the armature or field circuit, but not of both. A diagram of connections for a regulator designed to reverse the armature connections is shown in Fig. 192. If the lever is moved to the left until it makes contact at points *b*, *e*, and *k*, the current entering at *a* will pass through the resistor to *b*, then through conducting bar on lever to *e*, thence to *f*, *g*, and motor armature to *h*. From *h* it passes to *K* and by way of arm to *O* the other side of the line. If the lever is moved to the right, the current on entering at *a* passes through the resistor to *b*, then through the connector to *c* where it enters the conducting bar on the controller arm. From *c* it goes to *i*, *j*, *h* and enters the armature in the opposite direction after which it passes to *g*, *l* and by way of lever to *O*. As the shunt field remains permanently connected to the line the direction of rotation is reversed every time the controller arm is moved from the left to the right of the vertical position or *vice versa.*

here are many other types of controllers, their design depending on the service to be performed.

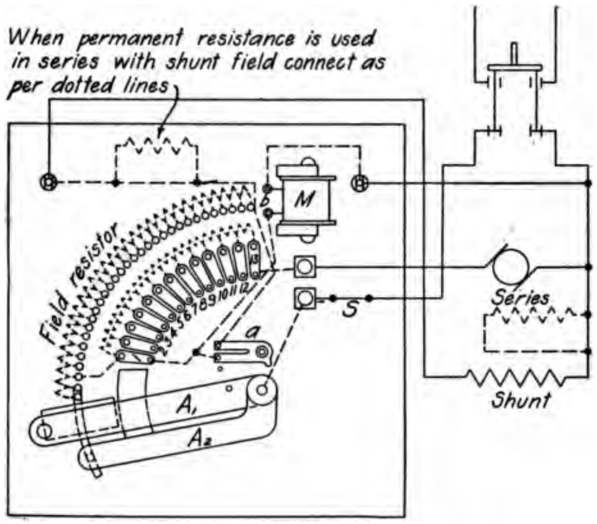

FIG. 191.

207. Precautions To Be Observed in Operating Direct-current Motors.—As direct-current generators and motors are mechanically and electrically alike, it is evident that in their operation

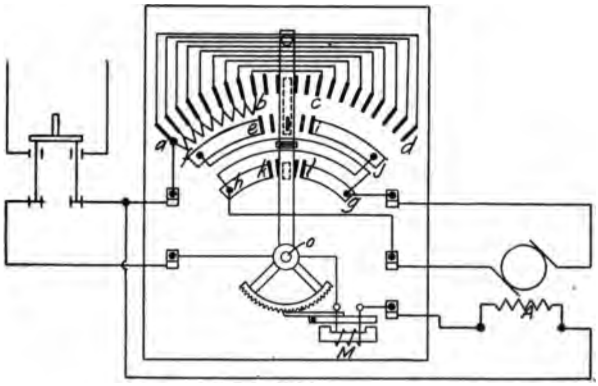

FIG. 192.

motors should receive the same care and attention as generators. In starting, caution is necessary. If the motor does not start

promptly when the rheostat arm has been moved to the third contact point, it is likely that the field circuit is broken or the motor is overloaded. The resistance of a starting rheostat is designed to carry the line current for only a short time, during starting. The motor should not be permitted to run for any length of time unless the rheostat arm is in the running position. To stop the motor, the line switch is opened and the rheostat arm will set itself automatically at the starting position.

208. Troubles Peculiar to Motors.—Motors are subject to the same troubles as generators, such as sparking at the brushes, overheating, etc. Owing to the manner of operation certain symptoms of faults are peculiar to motors only. The symptoms of most motor troubles other than those that are common to generators also may be grouped under the following heads:

1. Failure to start.
2. Too low speed.
3. Too high speed.

1. *Failure to Start.*—When a series motor fails to start it is either overloaded or the line circuit is broken. An open field circuit may be responsible for failure to start of shunt or compound motors. The speed of the series motor varies so greatly with load that too low or too high speed has no significance. It is only the shunt or compound motor to which the terms can apply.

2. *Too Low or Too High Speed.*—This can apply only to motors with a shunt winding.

When the speed of a shunt motor is too low it may be due to an overexcitation of the field, but more likely to an overload, or a combination of heavy load with underexcited field. Excessive speed in a shunt motor is generally due to underexcitation of the field or a wrong position of the brushes. Misplaced brushes cause a weakening of the field, resulting in high speed and sparking at the brushes.[1]

[1] See "Management of Electrical Machinery" by CROCKER and WHEELER; "Motor Troubles" by E. B. RAYMOND.

CHAPTER XV

OPERATION OF THREE-WIRE SYSTEMS

209. Introduction.—Three-wire systems were first supplied by two like generators connected in series as indicated in Fig. 193. Such a connection of generators would operate quite satisfactorily so long as the load was balanced, but it necessitated the continuous operation of two machines no matter how small the load.

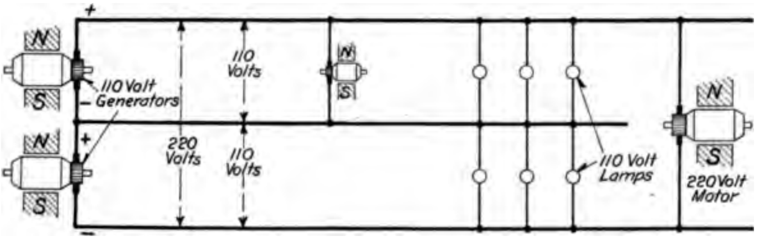

FIG. 193.

On unbalanced load, the voltage between the neutral and outside wires differed greatly unless close attention was given to its regulation. To secure automatic regulation different schemes have been employed.

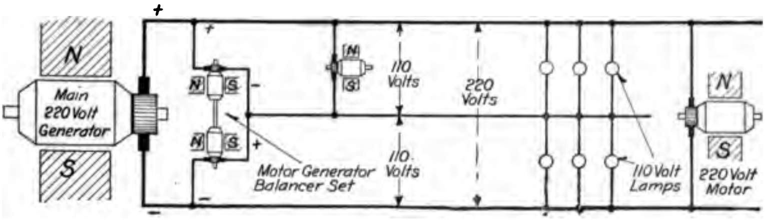

FIG. 194.

210. Balance Sets.—The next step in the evolution of the three-wire system was the use of a two-wire generator whose voltage was equal to that desired across the outside wires. In parallel with this generator were connected two similar direct-connected machines in series as shown in Fig. 194. The neutral

wire was connected to the junction point of the electrical circuits of the motor-generator set, as these machines are commonly called. The balancer set may be connected in several different ways, and the machine may be either shunt or compound-wound.

211. Operation of Shunt Balancer Set.[1]—Two similar shunt machines each wound for one-half the voltage of the main generator may be used to automatically balance the voltage on the two sides of a three-wire system. The operation of such a set is as follows:

In Fig. 195 the machine in the more heavily loaded side is designated by G, and that in the other side by M. The significance of this designation will presently appear. When the connections of the shunt field are as indicated in the diagram, the excitation of the two machines is the same, and as they run at the

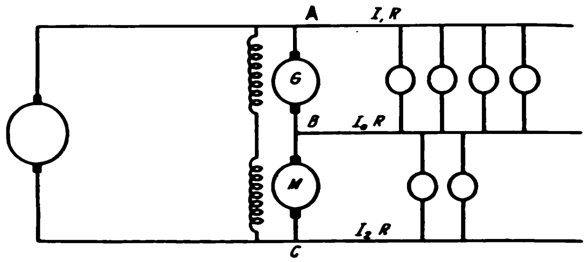

Fig. 195.

same speed, the counter electromotive forces of the two must be equal. Due to the unbalanced load, the pressure between A and B is less than that between B and C, hence the difference between E_1 and the counter pressure of machine G is less than the difference between E_2 and the counter pressure of machine M, consequently, a larger current flows through M than through G. This larger current will cause machine M to speed up, increasing the counter pressures of both G and M. E_1 and E_2 are the line pressures between AB and BC, respectively.

The unbalancing may be so great as to cause pressure E_1 to drop below the counter pressure of machine G. Under this condition the armature current in G will reverse and it will operate as a generator boosting the voltage on the more heavily loaded side. To understand exactly what takes place let us make the following assumptions:

[1] *Electric Journal*, vol. 9, p. 1036.

Let E = pressure of main generator,
E_g and E_m = counter pressures of machines G and M, respectively,
R_a = resistance of each armature,
I_g and I_m be the currents in machines G and M respectively.

Then $E = E_g + E_m + (I_g + I_m)R_a$.

When the load is balanced $E_g = E_m$ and I_g is identical with I_m. We then have

$$
\begin{aligned}
E &= 2E_g + 2I_gR_a \\
&= 2(E_g + I_gR_a) = 2E_1 \\
&= 2(E_m + I_mR_a) = 2E_2
\end{aligned}
$$

or $E_1 = E_2$.

When the load is unbalanced then E_1 is no longer equal to E_2 unless the balancer set compensates for the difference. We may assume two cases.

Case I.—Slight Unbalancing.—If the unbalancing is not sufficiently great to cause E_1 to drop below E_g, both machines will operate as motors but with different armature currents. Under this assumption $I_1 = I_2 + I_o$

$$I_m = I_o + I_g.$$

Then $E_1 = E_g + I_gR_a$

and $E_2 = E_m + I_mR_a$

$$E_2 - E_1 = E_m - E_g + (I_m - I_g)R_a.$$

But $E_m = E_g$ as the field excitation is the same, and

$$I_m - I_g = I_o.$$

Then $E_2 - E_1 = I_oR_a$.

As I_o is small, the unbalancing will not be great.

Case II.—Load Greatly Unbalanced.—Under this assumption E_1 may drop below E_g and the current in machine G will be reversed. It will then operate as a generator and M will operate as a motor. The voltage relation will then be as follows:

$$E_1 = E_g - I_gR_a$$

$$E_2 = E_m + I_mR_a$$

and $I_o = I_m + I_g$.

Whence

$$
\begin{aligned}
E_2 - E_1 &= E_m - E_g + I_mR_a + I_gR_a \\
&= R_a(I_m + I_g) \\
&= I_oR_a \text{ as before.}
\end{aligned}
$$

The actual unbalancing is, of course, greater than in case 1, because the current in the neutral is larger.

Since E_2 is greater than E_1 the difference between E_2 and E_1 may be reduced still further by connecting the shunt field of G across E_2 and the shunt-field winding of M across E_1 as shown in Fig. 196. When such a connection is employed, the field of the

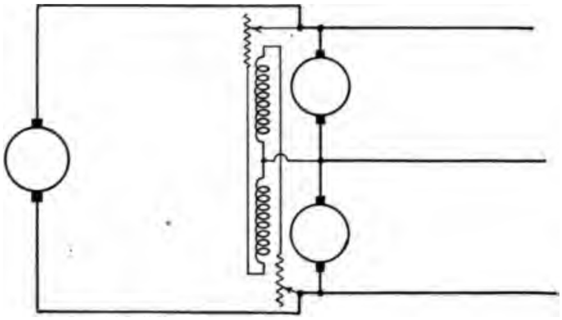

FIG. 196.

machine acting as a motor is weakened which raises its speed, and the generator field is strengthened. The voltage regulation is thus better than when the connections shown in Fig. 195 are used.

212. Compound-wound Balancer Set.—Compound balancers consist of two similar compound-wound machines rigidly con-

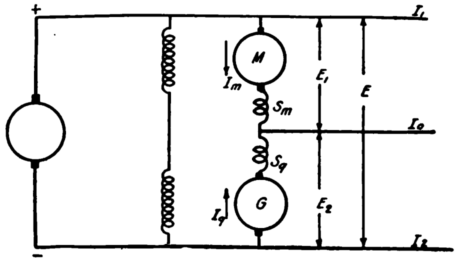

FIG. 197.

nected together mechanically, and in series electrically just as the shunt-wound balancer set. There are several ways in which the shunt and compound windings may be connected to each other and the mains. Four different schemes of connection are shown in Figs. 197, 198, 199, and 200.

Under unbalanced load conditions one of the machines oper-

ates as a motor and the other as a generator like the shunt balancer set, but their electrical characteristics are somewhat different. The machine operating as a motor has the characteristics of a differential motor while the other has those of a cumulative compound generator. That is, the magnetomotive force of the series winding opposes that of the shunt winding on

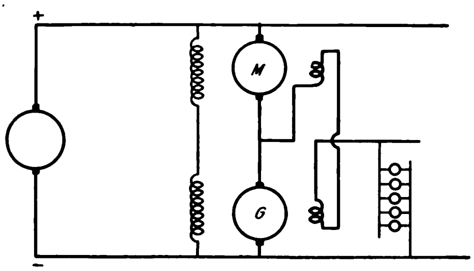

FIG. 198.

the motor and assists that on the generator. The result is that the counter electromotive force, or induced electromotive force, of the motor is reduced or its speed is increased, and the induced electromotive force of the generator is increased by an amount approximately equal to the I_aR_a drop in the machine. As a consequence practically an equal division of the total voltage is

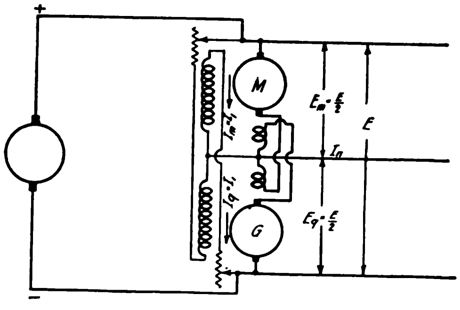

FIG. 199.

maintained between the neutral and the outside wires within the normal operating range of the machines.

When the scheme of connections shown in Fig. 197 is used, on balanced load the two machines operate as differential motors in series. On unbalanced load, as indicated, the upper machine becomes a motor and the lower machine operates as a generator.

Since the current in the series winding of the motor is greater than that in the series winding of the generator, this decrease in the motor field flux will exceed the increase in the field flux of the generator. The differential action of the series winding on the motor is followed by a rise in speed. If the unbalancing is great, the operations of the motor may become unstable.

When the scheme of connections shown in Fig. 198 is employed on balanced load, the two machines operate as shunt motors. With the load unbalanced, as indicated, the upper machine becomes a motor and the lower machine becomes a generator. The current in the neutral flows through the series windings of both machines, accordingly the difference between the decrease in the motor flux and the increase in the generator flux will be less than when the connections of Fig. 198 are employed. The braking action of the generator will be greater also and consequently there will be a smaller change in the speed of the motor

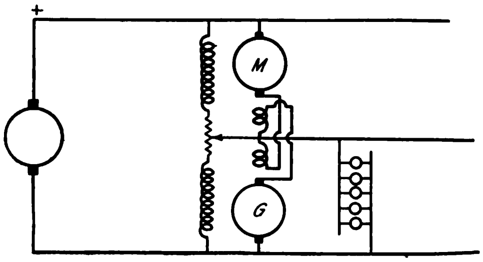

FIG. 200.

for the same degree of unbalancing. The diagram of connection, Fig. 199, shows both series and shunt windings crossed. The machines when so connected operate as compound motors on balanced load. When operating as a motor generator on unbalanced load, the cumulative compounding action of the generator series field is stronger than the differential action of the series winding of the motor. This is also true when the scheme of connections of Fig. 200 is employed, in which the shunt windings are not crossed. There is thus a still smaller change in speed for a given degree of unbalancing than when either of the two previously mentioned schemes are used.

When the shunt-field windings are connected to the neutral the shunt excitation of either machine may be adjusted independently of the other which gives greater flexibility to the system.

213. Operating Characteristics of Compound Balancer Sets.—On account of the service requirements compound-wound dynamos intended for balancer sets must fulfill certain definite requirements. In the first place, the two machines must be exactly alike, and must be designed for the service, that is, the electric and magnetic characteristics of one must be the duplicate of those of the other. Since either machine must operate as a motor or generator satisfactorily, there must be slight distortion of the field flux with load, or service, in order that the brushes may remain in fixed positions. As the armature current is larger when the machine is operating as a motor, the brushes may be shifted slightly backward. Commutating-pole machines are well suited for balancer sets.

274. Stability and Compounding.[1]—Stable operation of compound-wound balancer sets is obtainable under all reasonable

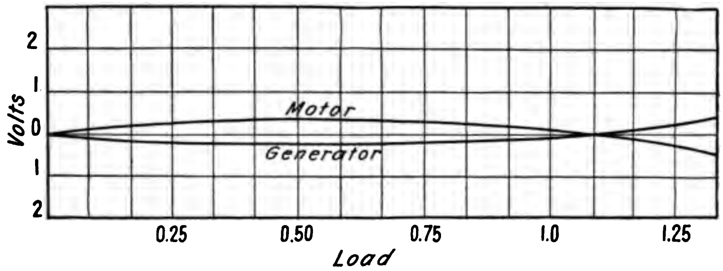

FIG. 201.

conditions of service if the units of the set are designed for the service and if the proper field connections are used. In general, the most stable performance results when there is the least distortion of the field flux on the machine operating as a motor. If this is small, there will be required a small differential action of the series winding, and consequently the working range of the magnetization curve will likewise be small. The resistance of the armature and series windings should be low, and the series windings of the two machines should be crossed so that compounding takes place with a minimum change in speed. With shunt fields crossed, the inequalities in voltage on the motor and generator side, between no load and full load, are negligible, in sets of moderate or large capacity. With shunt fields connected straight and their junction point tapped to the neutral, the devia-

[1]A. C. LANIER: *Electric Journal*, vol. 9.

tion of voltage from a straight line is usually very slight. A typical voltage regulation curve is shown in Fig. 201.

The usual practice is to wind the balancer sets for flat compounding, but requirements of service may necessitate overcompounding. The degree of overcompounding that may be obtained is limited by the requirements of stability on overloads which may occur. However, overcompounding of about 5 per cent. is obtainable.

275. Practical Operation.—Balancer sets are put into service in exactly the same way as a motor. The shunt fields are connected in series across the outside wires, with the junction point

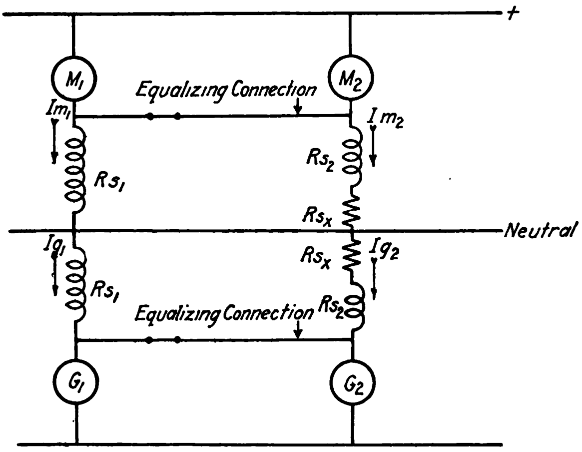

FIG. 202.

of the two windings disconnected from the neutral of the set. The line switches are closed and the armatures are brought up to speed by a suitable rheostat.

The next step is to connect the junction point of the two shunt windings to the junction point of the armature windings and by means of the field rheostats, when these are used, the voltage is adjusted for no-load balance. The switch connecting the neutral wire to the set is then closed and the machines automatically divide the load and maintain balanced voltage.

"Similar compound-wound balancers will operate satisfactorily in parallel, if proper interconnections are provided. When the series fields are connected in the neutral circuit, one equalizer connection is required between armatures; if the series fields are

connected in the circuits of the individual machines, two must be used. For proportional division of current on all loads without rheostatic adjustment, the two sets must have similar compounding curves, and equal *IR* drops in the parallel pairs of series fields of the two sets when each field is carrying the current required for proper compounding; *i.e.*, the same current as the armature in whose circuit it is connected. Any wide departure from the proper value of currents in the series coils of the two balancer sets will cause objectionable disproportion in division of the load between the two sets with varying values of total unbalanced current. In such cases, proportionate division of current in the series coils can be secured by connecting, in series with the coils of one set Fig. 202, a resistance R_{sx}, whose value shall satisfy the equations:

$$I_{m1}R_{s1} = I_{m2}(R_{s2} + R_{sx})$$

and

$$I_{g1}R_{s1} = I_{g2}(R_{s2} + R_{sx})$$

where the symbols have the following significance:

I_{m1}, I_{m2} = motor currents in sets 1 and 2 respectively,

I_{g1}, I_{g2} = generator currents in sets 1 and 2 respectively,

R_{s1}, R_{s2} = series field resistances of sets 1 and 2,

and

R_{sx} = the auxiliary resistance to be connected in series with the series coils of one set.

276. Protection.—"The design of a system of protection for three-wire circuits and of auxiliary balancing apparatus can not follow inflexible rules, each case requiring treatment more or less on its merits. In general, two phases of the question must be kept distinct, the protection of the three-wire circuit and of the receivers connected to it, and the protection of the balancer set. Determining factors in the selection of a scheme of protection are—sensitiveness to voltage variation of the receivers connected to the system, as incandescent lights, motors, etc., size of systems and of balancing outfits used, importance of uninterrupted service, first cost, etc.

"Small equipments have been frequently installed without automatic cutouts for the balancer, knife switches only being provided for disconnecting the set from the system. Where incandescent lamp load is served, reasonable voltage balance is maintained up to the flash-over load of the balancer. Should

the set be disabled by an excessive short time overload, however, both receivers and balancers suffer.

"A single-pole circuit-breaker in the neutral lead from the balancer, operating an overload trip on the main generator or feeder circuit-breaker gives more complete protection for both receivers and balancer sets. Some form of differential voltage relay may also be used which will trip the main circuit-breaker when a predetermined voltage unbalance is exceeded; in this case protection for the balancer can be provided independently by the use of suitable fuses or circuit-breakers. In general, on motor load, the chief attention can be directed to the protection of the balancer.

276A. "Selection of Balancer Equipments.—The full-load rating of balancer sets is usually given in terms of unbalanced current supplied to the neutral wire at a specified line and neutral voltage. In general, for lighting circuits the balancer may be selected to provide for 10 per cent. unbalance. The balancer capacity should, however, be determined on the basis of the half-voltage load connected between the neutral and the outer wires rather than on the main generator capacity, where information is available.

"On large systems where the circuits can be closely balanced relatively small balancer capacity is required, while in small isolated plants the converse is usually true. Other classes of service, such as for motor drive, battery charging, etc., frequently occur with widely varying degrees of load unbalancing; such applications require special analyses, both as to unbalanced capacity required and the most desirable type of balancing apparatus."

277. Three-wire Generators.—The use of three machines reduces to some extent the economy of a three-wire system. The many objections that could be raised against the use of a balancer set are in a great degree obviated by the development of three-wire generators. The difference between a three-wire direct-current generator and a standard two-wire generator consists in the addition of a slip ring or rings to the commutator and connecting these slip rings to symmetrically located points of the armature windings, and replacing the balancer set by a balancing coil or coils.

While the foregoing general statement applies in all cases the exact manner in which it is carried out in practice differs somewhat with different manufacturers. The principle in its simplest

form is illustrated in Fig. 203. This shows a two-pole ring armature machine. Two slip rings *M* and *N* connected to two diametrically opposite points of the armature winding are mounted on the shaft. Brushes resting on these rings are connected to a coil *BA* the middle point of which is connected to the neutral wire. It has been shown that the electromotive force induced in the armature of a direct-current generator is alternating, but is rectified by the commutator. When the armature is connected to slip rings as shown in the diagram alternating current will flow in the coil *BA* and the potential of the middle point *O* is always midway between the potentials of the points *B* and *A*, and hence midway between the potentials of brushes *E* and *F* as the poten-

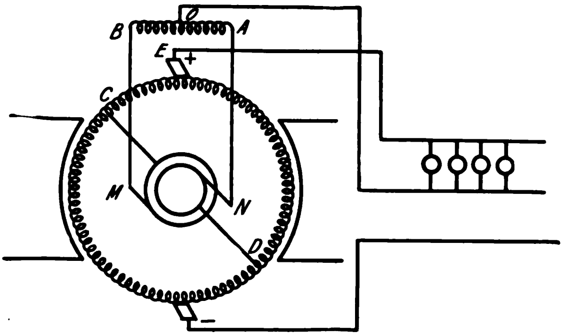

FIG. 203.

tials of *C* and *D* are always symmetrical with reference to the potential of the brushes *E* and *F*. The alternating current through the coil *BA* is very slight as the coil is wound upon an iron core and is thus highly inductive.

When the load is unbalanced, as indicated in the diagram, the current in the neutral will tend to divide at the point *O* inversely as the resistance of the two paths, *OANDE* and *OBMCE*, from *O* to the positive brush. The relative resistance of these two paths will depend upon the position of the armature at any instant as the armature rotates. This would produce a pulsating current in the leads *BM* and *AN*. This tendency of the current to divide at the point *O* in the manner suggested is prevented by the transformer action of the balance coil. When the current in *OA* increases, the flux in the iron core of the coil is increased, and this in turn induces an electromotive force in *OB* in such a direction as to increase the current in *OB* and decrease that in

OA. This action allows a slight pulsating current to flow in OB and OA, but this is so slight as to be negligible. The neutral current, therefore, divides almost equally between OA and OB no matter what the position of the armature. If R_a is the resistance of the armature between the brushes and if R_b is the resistance of the balance coil and one lead from C to O, and from D to O respectively, the voltage drop from O to C is $R_b\frac{I_0}{2}$. It can be shown that the average voltage drop in the armature from C to E as the armature rotates is $\frac{I_0}{2}\frac{R_a}{3}$. The total voltage drop from O to E is $\frac{1}{2}I_0\left(\frac{R_a}{3} + R_b\right)$ volts.

Balance coils are designed to carry a neutral current whose value is not over 25 per cent. of the full-load current in the out-

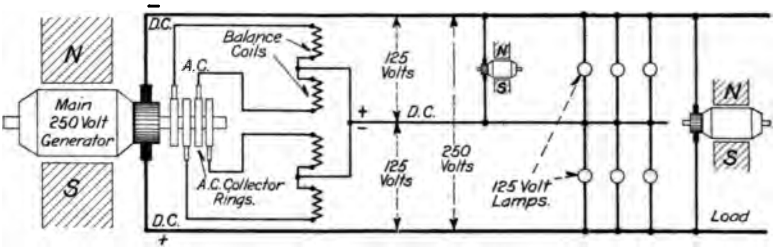

FIG. 204.

side wire. As the full-load armature drop is usually limited to about 3 per cent., it follows that the voltage drop from O to E due to the unbalanced current is small, and that the difference between the voltages on the two sides of a three-wire generator depends principally upon the resistance of the balance coils and leads which evidently should be low. This difference in voltage need not exceed 2 per cent.

In the diagram of Fig. 203, only one balance coil is shown. This represents the practice of the Ridgway Dynamo and Engine Co. The Westinghouse Electric and Manufacturing Company employs two balance coils connected as shown in Fig. 204. This arrangement has the advantage that the distribution of the currents in the armature on unbalanced load, and the consequent heating, is more uniformly distributed than with only one coil. The principle of operation is the same in either case.

The balance coils are wound upon a laminated iron core and

placed in an iron case similar to a transformer case, Fig. 205. These may then be mounted on the back of the switchboard or some suitable place in the station room.

Fig. 205.

Fig. 206.

The practice of the General Electric Company differs from that described above in that only one collector ring is used for obtaining the neutral connection. The balance, or compensator, coils are wound upon a circular magnetic core which is then

mounted on a cast bracket which is bolted securely to the back end of the armature spider, Fig. 206.

The compensator windings are connected to the armature windings at symmetrically located points, and the neutral connection is made through the spider to a single collector ring mounted on the outer end of the commutator shell. The principle of operation is the same as that of the external compensator.

278. Auxiliary Armature Windings.—A somewhat different scheme of securing balanced voltage is that employed by the Crocker-Wheeler Company. The essential elements of this scheme are shown in Fig. 207. As here shown an auxiliary wind-

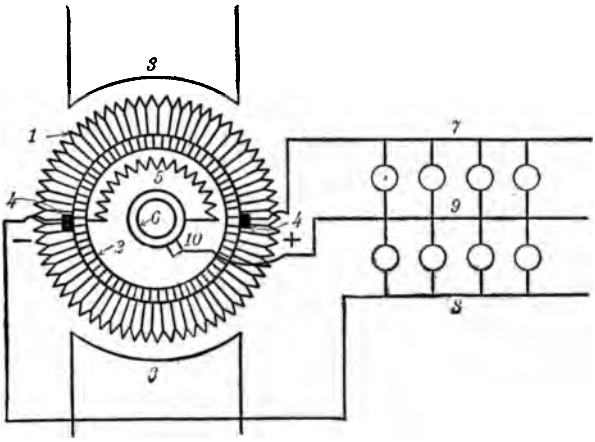

FIG. 207.

ing is placed on the armature, one end of this is connected to the main armature winding and the other to a slip ring, with which a brush makes contact. The auxiliary winding contains one-half the number of turns of the main winding in series between each positive and negative brush.

The voltage between the slip ring and either generator brush will be just one-half the generator voltage. When the auxiliary winding is in the position shown all of this voltage is generated in the auxiliary winding. At any other position of the armature the voltage between the neutral and either outside wire will be due to that induced in the auxiliary winding plus that induced in the armature coils which are between the connection of the two coils and either brush, so that at any position of the arma-

ture the potential of the slip-ring brush is midway between the potentials of the commutator brushes.

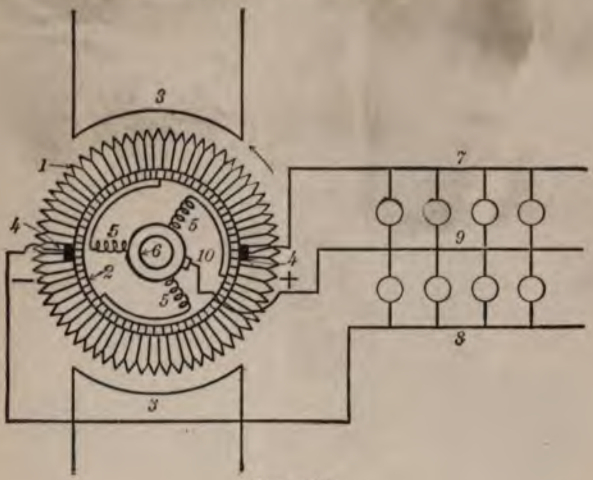

Fig. 208.

The single-phase winding, as that shown in the diagram is called, has not proved entirely satisfactory in practice on account

Fig. 209.

of fluctuating voltage induced in it which caused flickering. To remedy this difficulty a winding distributed over the armature core is used. This is shown in Fig. 208. This winding usually

consists of three or more coils symmetrically spaced and connected to the main winding and slip ring.

A Crocker-Wheeler three-wire generator armature is shown in Fig. 209. A complete generator is shown in Fig. 210.

FIG. 210.

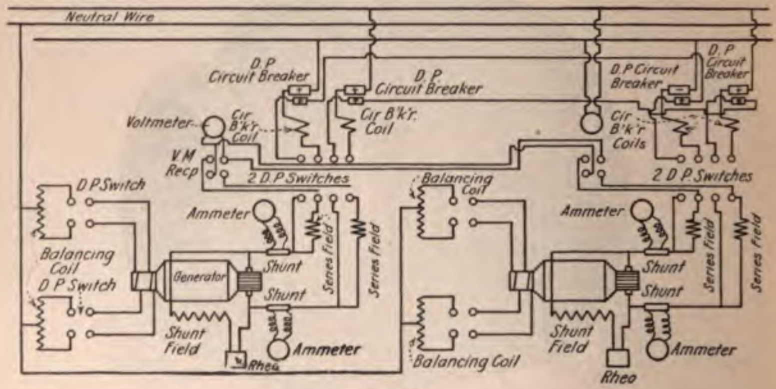

FIG. 211.

279. Three-wire Generators in Parallel.—Three-wire generators may be operated in parallel with each other and also in parallel with two-wire machines. It is unnecessary to synchronize or to connect in parallel the alternating-current sides of the armatures. The important condition to be fulfilled in operating

any combination of two-wire and three-wire generators in parallel is that the machines be of the proper voltage, and that suitable equalizer connections be made.

The switchboard connections for operating two three-wire generators in parallel together with all necessary instruments are shown in Fig. 211.

Three-wire generators may be compound-wound, or they may be built with commutating poles. When either of the above-mentioned windings is employed, it is divided into two equal sections; one section is connected in series with each of the outside wires. That is, all of the series winding on the north poles is connected in series with the positive brush and all of the series winding on the south poles in series with the negative brush. When commutating poles are used the winding is grouped in the same way.

CHAPTER XVI

SELECTION AND INSTALLATION OF DYNAMOS

280. Principles Governing the Selection of a Dynamo.—In selecting a dynamo, the particular type, capacity, and voltage of a machine will depend upon the character of the work it is to do. Each and every case must be separately considered. There are, however, some general considerations that hold in every case, and apply to motors and generators alike. Among these may be mentioned the following.

281. Construction.—The construction of a machine should be in accordance with approved standards. The material should be of the best for that type and class of machine and the workmanship first-class in every respect. The finish should be durable and pleasing in appearance. It should also be of such a nature as to harmonize with other machinery or equipment in the room. The construction should be as simple as possible in all its parts. No complicated features unless absolutely essential should be tolerated. The number of screws, bolts, and nuts should be reduced to a minimum, and they ought always to be provided with some locking device to prevent them from becoming loose. The brushes should be accessible, easily cleaned, and self-feeding; the bearings should be self-aligning and self-oiling. Every feature of the machine that will reduce the amount of attention to a minimum should be carefully considered, and that machine chosen which will require the least attention.

Several companies now make what are known as standard types of machines and in most cases it will be preferable to select a machine of this type. By so doing repair parts can readily be obtained and the machine will be cheaper than one of special design. Where close regulation is necessary, some automatic regulator should be provided. What form the regulator should take will depend upon the work. In many cases the voltage regulation will be the important feature to consider; while in other cases the current, or in case of motors, the speed is the important factor. The capacity in every case should be ample for the work to be done.

282. Standards for Direct-current Machines.—To insure uniform results in operation with reference to limitations of output as dictated by (*a*) operating temperature, (*b*) mechanical strength, (*c*) commutation, (*d*) insulation strength, (*e*) efficiency, and (*f*) regulation, the American Institute of Electrical Engineers has adopted and promulgated a set of Standardization Rules[1] with which the manufacturers of standard electrical apparatus are expected to comply. One of the rules provides that all machines be rated, that is, that the output or load which the machine is capable of developing or carrying under certain specified conditions be marked on the rating plate. There are in practice three methods of rating electrical machinery: the continuous, the short-time, and the nominal.

The *continuous rating* of a machine is the output expressed in kilowatts or horsepower which the machine will deliver continuously without exceeding the limitations of temperature, etc., mentioned above. The continuous rating indicates the load which the machine will carry continuously without any reserve overload capacity.

The *short-time rating* is applied only to machines which are to be operated intermittently, or only for short periods of time. A machine rated for short time service shall be able to operate at its rated output during a limited period to be specified in each case, without exceeding any of the limitations referred to above.

Railway motors and sometimes railway substation apparatus which may be called upon to carry overloads for short intervals are sometimes given a nominal rating. The *nominal rating* specifies the load which the machine will carry continuously and still have certain reserve overload capacity for a specified time. The present tendency is to rate all electrical machinery on the continuous carrying capacity basis.

283. Foundation.—In order that a machine may operate satisfactorily, great care must be exercised in the construction of the foundation. Each machine should have its own foundation in order that the vibration of one machine may not be transmitted to any other. The foundation for the machine should be entirely separate from that of the walls and other parts of the building.

The transmission of vibrations from one machine to another, or from one building to another, is determined to a great extent by

[1] These rules can be obtained from the Secretary of the Institute.

the character of the ground upon which the foundation rests. Sand or soft earth transmits them poorly; firm earths transmit them quite well, while rock almost perfectly. In cases where the transmission is to be obviated, various materials have been used to deaden them, such as sand, wood, hair-felt, mineral wool, and asphalt concrete. In rock or firm earth one plan is to excavate a pit 2 or 3 feet deeper and 2 or 3 feet wider on all sides than the foundation proper. A bed of sand of some thickness is then put into the pit and the foundations are built upon this, the

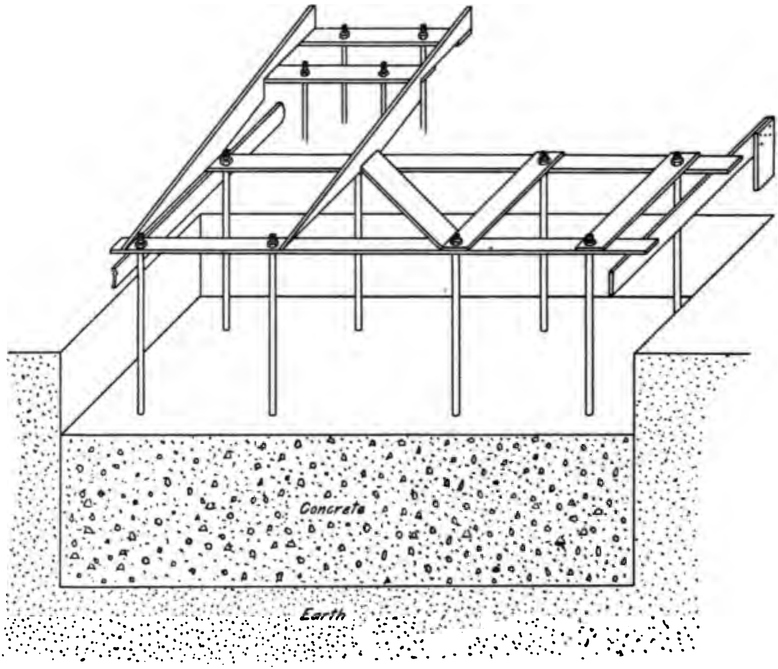

FIG. 212.

space around being filled with sand. When the foundation is to be constructed on solid rock, where there is danger of vibration transmission, the rock may be excavated several feet deeper than the foundation, and filled in with hair-felt or mineral wool upon which the foundation is built. Another solution of the problem is to use bituminous or asphalt concrete for the lower foot or two of the foundation, the remainder being ordinary concrete or brickwork, with a stone cap.

The machine foundation proper consists of a mass of brickwork,

stone masonry, or concrete upon which the machinery is placed. For the purpose of holding the machinery firmly in place, foundation bolts are built into the foundation passing entirely through the mass. The correct position for the foundation bolts is determined by means of a wooden template as shown in Fig. 212. The brickwork for machinery foundations should consist of hard-burned bricks of good quality, laid in good cement mortar. The top of the foundation should be perfectly level, or conform to the bedplate of the machine. If this is not so, the bedplate may spring and throw the bearings out of line, or otherwise interfere with the operation of the machine.

284. Mechanical Connections.—There are various methods used in connecting a generator with its engine or other prime mover. Among the most common methods are the following:

(*a*) Direct connection.
(*b*) Belting and rope connection.
(*c*) Chain connection.
(*d*) Toothed gearing.

(*a*) *Direct Connection.*—A generator is said to be direct-connected when its armature is mounted upon the driving shaft of its engine. When so connected both engine and generator should be mounted upon the same bedplate, if the size permits. In selecting a generator to be driven by an engine or some other prime mover, two things must be carefully considered; the speed and capacity of the generator and the speed and capacity of the prime mover. In case the generator is to be "direct-connected" to its engine they will both be compelled to run at the same speed. Since the most efficient peripheral speed of a generator armature is high, and the speed of a reciprocating engine is low, some difficulty is experienced in obtaining the desired speed for the two machines. The capacity of a given-sized dynamo depends upon the speed at which it is to be driven. Thus a generator to be direct-connected to a slow-speed engine will have to be larger for the same output than if it is to be belt-driven at a high speed. It is of prime importance in making comparison of prices on generators or motors of given rated output to consider the speeds at which the machines are to be driven.

The direct connection being the simplest, other things being equal, it is to be preferred.

When the prime mover is of the high-speed type, as the steam turbine, direct connection is preferable to any other form. In

this case, when properly designed, the engine and generator can be operated at their most efficient speed.

(*b*) *Belt Connection.*—When the generator or motor is not direct-connected, some form of "belt drive" is usually used. While the principles of belt drive are quite well understood a few of the main principles will, however, be given. Leather belting is usually the most reliable and satisfactory for general use, except in cases where the generator pulley is near the driving pulley, where some form of chain drive is preferable.

The ordinary rule for the amount of power that can be transmitted by a belt is as follows: A single thickness belt will transmit 1 horsepower for each inch of its width when travelling at a speed of 1,000 feet per minute. This statement is based on the assumption that the belt is in contact with its transmitting pulley around one-half of its circumference. To secure an arc of contact as great as possible, it is advisable to have the belt run over, that is, to have the loose side of the belt on top, and the machines and engine relatively far apart.

Any formula for determining the width of a belt for transmitting a given horsepower is at best only approximate. The following is usually given for a single-thickness belt:

$$w = \frac{Hp. \times 1{,}000}{S \times C}$$

where w is the width of the belt in inches; $Hp.$ is the horsepower to be transmitted; S is the speed of the belt in feet per minute; and C is a factor depending upon the arc of contact. For an arc of 180°, $C = 1$; for 135°, $C = 0.84$; and for 90°, $C =$ only 0.64. Double belting will transmit 1.5 times as much as single belting. A belt should not be operated at too high a tension for this causes excessive bearing friction, stretches the belt unnecessarily, and may break the pulley.

Length of Belt.—The best and most accurate method of determining the length of belt for a given installation is by actual measurement. When this is impossible, a drawing of the installation may be made as shown in Fig. 213 and the length of belt calculated as follows:

Let O and O' be the centers of the driving and driven pulleys,
Let R = radius of larger pulley,
Let r = radius of smaller pulley,
Let d = distance between their centers.

Then $\sin \alpha = \dfrac{R - r}{d}$.

The length of belt between *ab* and *cd* is $2d \cos \alpha$. The length of belt for one-half the circumference of the larger pulley is πR.

The angle $eoa = cof =$ angle α.

Arc $ea = R\alpha$ if α is expressed in radians. If α is expressed in degrees, then

$$\text{arc } ea = 0.01745R\alpha.$$

The length of belt in contact with large pulley is, therefore,

$$\pi R + 2 \times 0.01745R\alpha = R(\pi + 0.0349\alpha).$$

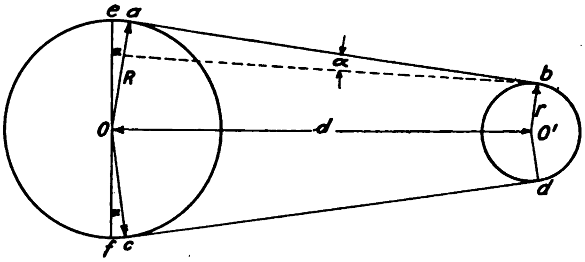

FIG. 213.

Similarly, the length of belt in contact with the small pulley is

$$r(\pi - 0.0349\alpha).$$

The required length is

$$L = R(\pi + 0.0349\alpha) + r(\pi - 0.0349\alpha) + 2d \cos \alpha.$$

It is thus only necessary to measure accurately the distance d.

For crossed belts by a similar method of reasoning we get

$$L = (R + r)(\pi + 0.0349\beta) + 2d \cos \beta$$

where β is determined by the relation

$$\operatorname{Sin} \beta = \frac{R + r}{d}.$$

Results that are accurate enough for practical purposes may be obtained by the application of the following formula:

$L = \pi(R + r) + 2\sqrt{d^2 + (R - r)^2}$ for straight belts, and
$L = \pi(R + r) + 2\sqrt{d^2 + (R + r)^2}$ for crossed belts.

Example

A generator is to be driven by an engine with a driving pulley 5 feet in diameter; if the generator pulley is 18 inches in diameter and the distance between the center of the two pulleys is 25 feet, what length of belt is required?

Solution.—Using the more accurate formula we have

$$L = R(\pi + 0.0349\alpha) + r(\pi - 0.0349\alpha) + 2d\cos\alpha.$$

But $R = 30$ inches
$r = 9$ inches
$d = 300$ inches.

Hence $\sin\alpha = \dfrac{30 - 9}{300} = 0.07$

and $\alpha = 4°$

Then
$$\begin{aligned} L &= 30(3.1416 + 0.0349 \times 4) + 9(3.1416 - 0.0349 \times 4) \\ &\qquad + 2 \times 300\cos 4°. \\ &= 724 \text{ inches} \\ &= 60 \text{ feet 4 inches for a straight belt.} \end{aligned}$$

For crossed belts the length is given by

$$L = (30 + 9)(\pi + 0.0349 \times \beta) + 2d\cos\beta.$$

$$\text{Sin}\,\beta = \frac{30 + 9}{300} = 0.13$$

and $\beta = 7.4°$.

Then
$$\begin{aligned} L &= 39(3.1416 + 0.0349 \times 7.4°) \\ &= 727.56 \text{ inches} \\ &= 60 \text{ feet 7.6 inches.} \end{aligned}$$

If the less accurate formulas are used we have for open belts

$$\begin{aligned} L &= \pi(39) + 2 \times \sqrt{300^2 + 21^2} \\ &= 723.9 \text{ or 724 inches as before.} \end{aligned}$$

For crossed belts the formula

$$L = \pi(R + r) + 2\sqrt{d^2 + (R + r)^2} \text{ gives}$$
$$\begin{aligned} L &= 3.1416 \times 39 + 2\sqrt{300^2 + 39^2} \\ &= 727.5 \text{ inches.} \end{aligned}$$

When the distance between centers of the two pulleys is large in comparison with the diameters of the pulleys the two sets of formulas give practically the same results.

Rope Connection.—Rope drive possesses certain advantages over the ordinary belting in that it is cheaper; a large amount of power can be transmitted with a given width of pulley; it is almost noiseless; it can be used for transmitting power over comparatively long distances; and also in cases where the power is to be transmitted at an angle, especially in a vertical direction.

The ropes may be made of cotton, or hemp. The manila hemp is the most widely used for transmission work.

The Multiple-rope and Continuous-rope System.—The multiple-rope system employs a number of single ropes running side by side. The advantages are: It can not be disabled by the breakage of one or two of the ropes; it takes up little space; and spare rope costs but little. The disadvantages are: The unequal tension in the ropes, and the difficulties of installation, because the ropes have to be spliced in place or the sheaves removed from the bearings. By using couplings instead of splicing the rope, these objections are nearly overcome. The coupling permits the installation of a rope in a brief time, and when the rope stretches it can be uncoupled and the slack taken up by twisting the rope until the proper tension is obtained on recoupling.

The continuous-rope system employs only one continuous rope which is wrapped around the sheaves the proper number of times, and then carried from the last groove of the driving sheave around a tension pulley to the first groove of the driven sheave or by a modification of this method. The advantages are: It is easily installed, there being but one splice; uniformity of tension in all strands or sections of the rope; and great flexibility. The disadvantages are: Complete shutdown when the rope breaks; the great cost of spare ropes; and the large space taken up by tension carriage.

The breaking strength of rope varies from 7,000 to 12,000 pounds per square inch of cross-sectional area. Experience has shown that best results are obtained when the tension in the taut or driving side is only 3 to 4 per cent. of the tensile strength. The most economical speed is from 4,000 to 5,000 feet per minute. At greater speeds than this the wear on the rope is excessive. The horsepower that a single manila hemp rope will transmit at different speeds may be calculated from the following equation:

$$Hp. = \frac{2}{3}\left(T - \frac{WV^2}{32}\right)\frac{V}{550}$$

where T = tension on driving side

= 200 diameter squared

= 200 D^2,

W = weight of rope per foot,

and V = speed in feet per second.

When transformed, the above formula may also be used for

calculating the diameter of a single rope required to transmit a given horsepower. By substituting $200D^2$ and $0.34D^2$ for T and W respectively, we get

$$Hp. = \frac{2}{3}\left(200D^2 - \frac{0.34D^2V^2}{32}\right)\frac{V}{550}$$

which when reduced gives

$$D = \frac{\sqrt{77{,}700 \times \text{Hp.}}}{\sqrt{(18{,}820 - V^2)V}}.$$

Example

What is the diameter of a rope required to transmit 42.5 horsepower if the rope is to move at a speed of 3,000 feet per minute?

Solution.—

$$D = \sqrt{\frac{77{,}700 \times \text{Hp.}}{(18{,}820 - V^2)V}}$$

$$V = 3{,}000 \div 60 = 50 \text{ feet per second.}$$

$$\text{Hp.} = 42.5.$$

Then

$$D = \sqrt{\frac{77{,}700 \times 42.5}{(18{,}820 - 2{,}500)50}}$$

$$= \sqrt{4.04}$$

$$= 2 \text{ inches.}$$

At best, formulas can give only approximate results as the conditions of operation are not always the same.

(*c*) *Chain Connection.*—Where the distance between the driving and driven machines is too short for belt drive and too far for gear connection some form of chain drive may be used. There are at the present three principal kinds of chains used; the roller chain, the block chain, and some form of the so-called silent chain. The efficiency of these chains is quite high and they are particularly useful where a positive connection is desirable, as between motors and heavy machine tools which they drive. This form of transmission requires no definite tension on the slack side of the chain, and hence the pressure on the bearings is much reduced for a given effective torque.

(*d*) *Toothed Gearing.*—This method is very little used for driving generators. It is, however, used almost exclusively for the connection of railway motors, and so will not be discussed here.

285. Switchboards.—Only the merest suggestions concerning switchboards and their equipment can be given. The design of

switchboards has become to a great extent standardized and manufacturers will furnish suitable designs for any practicable combination of machines. There are, however, certain essential instruments and elements in the equipment and design of every switchboard. The essential equipment may be grouped under the following heads:

(a) Controlling.
(b) Measuring.
(c) Protective.
(d) Switching or distributing.

The design of the switchboard consists in arranging and grouping this equipment in a convenient and harmonious manner. The switchboard should not only contain the necessary equipment

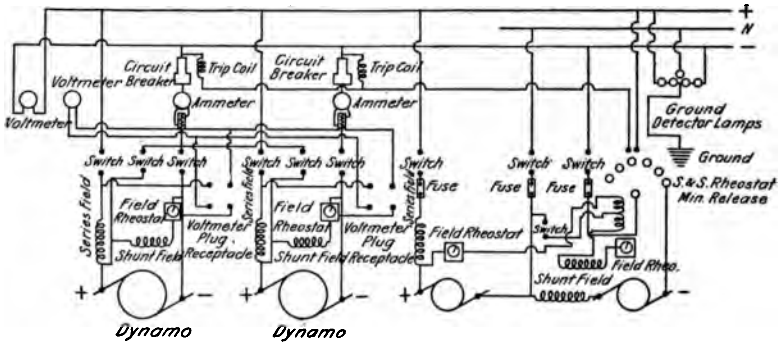

FIG. 214.

but it should be arranged in a balanced and pleasing manner and with reference to accessibility.

Fig. 214 shows the standard connections for a small direct-current equipment comprising two compound-wound generators and a balancer set for three-wire circuits.

(a) *Controlling Apparatus.*—For the installation shown in the diagram the controlling equipment is quite simple and consists merely of one field rheostat in the shunt circuit of each machine. For ordinary conditions the rheostat resistance is made equal to the shunt winding of the machine. For exceptional conditions requiring more than ordinary voltage range the rheostat resistance is made larger. Rheostats having a resistance two to four times that of the shunt-field winding are especially adapted for

use with some forms of automatic voltage regulators. In order to get small voltage variation between rheostat steps, the rheostat of lowest allowable resistance should be used, and it should be divided into as many sections as possible consistent with good design. The number of sections will vary with the size of the rheostat, the range being from 26 to 80. The rheostat must be able to dissipate 25 per cent. or more of the field loss continuously without overheating.

(*b*) *Protective Apparatus.*—For protective purposes one circuit-breaker is inserted in the negative lead of each generator. The capacity of this circuit-breaker must be equal to that of the generator. All of the current-carrying parts must have a rated capacity equal to the normal capacity of the circuit and must also have a suitable overload capacity.

There are connected in series with the busbars several incandescent lamps. Their number is such that under normal conditions half their rated pressure is applied to them, causing very little glow. The middle point of the series is connected to the ground. If either side of the line becomes grounded, the lamps on that side are short-circuited and full voltage causes the others to burn brightly, thus automatically indicating a ground. By opening the different circuits in turn and noting when the ground disappears, the faulty circuit can readily be located.

(*c*) *Measuring Equipment.*—For measuring the output of each generator an ammeter is also connected to the negative lead of each machine.

Two voltmeters are also necessary to complete the equipment. One is connected permanently to the busbars, while the other is connected to the voltmeter bus from the plug receptacles. The voltmeters are calibrated up to 25 or 50 per cent. in excess of the normal voltage.

(*d*) *Switching Apparatus.*—The diagram shows three single-pole, single-throw switches in the circuits of each generator. These may be replaced by one single-pole and one double-pole or one three-pole switch. Two-pole switches are seldom used in circuits designed to carry 2,000 or more amperes and the use of three-pole switches is limited to circuits of 1,600 amperes or less on account of the difficulty in operating them. The switch in the equalizer circuit is usually of the same capacity as the switches in the main circuits, but may be smaller, about one-half the capacity of the others.

The feeder circuits may be equipped in various ways. Double-pole switches are used in circuits of 2,000 amperes or less. If the load current is less than 600 amperes, enclosed fuses are used for overload protection. With circuits of greater capacity than 600 amperes or in which heavy momentary overloads are likely to occur, circuit-breakers are used.

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